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ALBERG, SANDRA LYNNE. The Use of Building Materials and Structural Systems in the Architectural Environment.

Just as the elements of the natural environment have an interrelated relationship, so the parts of the man-made environment have a similar interrelatedness. There is a growing tendency, therefore, to believe that the people who develop, design, and participate in these different parts of the man-made environment should be working together as a team for a total environmental design. Communication among these members is essential to this type of design, and there should be a common understanding of fundamental design vocabulary and principles.

Often times, interior designers are trained in the aesthetics and social implications of design, with little understanding of the more technical aspects. This project was undertaken to present simply information on one segment of design which interior design students may have little exposure to--structural principles, systems, and materials, which make up our architectural environment.

Structure is considered as the basis of all design, and yet it does not necessarily dictate the expression of form. There should be a certain inherent integrity between structure and form. To begin to appreciate more fully the way a building functions, one must understand some basic principles involved in structural design. Forces such as compression, tension, and shear are constantly acting upon and within a structure. These forces must be equally resisted if the structure is to remain standing or is to be able to be used. Some materials may be able to better resist certain forces than others, and each material, such as

wood or steel, has a specific design role for which it is to be used. Structural systems, such as the post-and-beam, or shell system, offer design alternatives for spanning space and enclosing shelter for man and his activities. Each system has unique characteristics and requirements.

This study has presented information on structure by written form and through correspending visual presentations. Slides were developed to illustrate principles, materials, and structural systems, for design students and adult audiences. An animated film clip was made with a different manner of approach to the problem of presenting technical information on structure in a simplified form, for use as either a classroom aid or an exhibit in itself for a younger or general audience.

THE USE OF BUILDING MATERIALS

AND STRUCTURAL SYSTEMS IN

THE ARCHITECTURAL

ENVIRONMENT

by

Sandra Lynne Alberg

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Approved by

Jane H. Crow

Thesis Adviser

APPROVAL SHEET

This thesis has been approved by the following committee of the Faculty of the Graduate School at The University of North Carolina at Greensboro.

Thesis Adviser Jane H. Crow

Oral Examination Committee Members D. Gordon Bennett

Nancy White

2/25/72
Date of Examination

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CHAPTER I

INTRODUCTION

Rationale

From every direction today one hears the alarming news of the deteriorating quality of our natural environment--destruction of wildlife habitat; depletion of our natural resources; over population; pollution of the air and water. With this recognition, however, has come a rallying to preserve, if possible, the ecological balance of man's natural surroundings. At the same time, man has been equally guilty of neglecting the environment in which he lives and moves--his man-made surroundings. His cities have grown in chaotic sprawls; endless ribbons of super highways cut across the landscape and divide cities, leaving a wake of competing billboards; buildings rise higher and higher, as if to blot out the sun; there is an incoherency and formlessness in much of these, his man-made surroundings--a sort of visual pollution.

One of the most outspoken critics of this visual insensitivity has been author and artist, Gyorgy Kepes. In his book, Education of Vision, Kepes bluntly states that our man-made environment

> . . . has not grown according to nature but has been shaped by one-sided and shortsighted interests. The appearance of things in our man-made world no longer reveal their character; images imitate forms; forms cheat functions; functions are robbed of their natural sources emanating from human needs. Our cities, our buildings . . . are often without visual integrity. The world that modern man has constructed by and large lacks sincerity and scale (14:1).

Just as in nature, there seems to be a delicate ecological balance, so in the man-made surroundings there is a same kind of balance between man and his man-made environment. When Kepes uses the term "vision," he means "our creative response to the world" (14:i) and he considers it to be fundamental in the formation of our physical and spatial surroundings. Conversely, one responds to, and develops his creative capacities from encountering the sensations and forms of the physical world around him. It is a reciprocal relationship: if he is out of balance with either his physical or perceived environment, he tends to lose his capacity to shape or structure his environment according to his needs.

Man's responsibility to himself and his man-made environment is to educate and make knowledgeable his sense of vision. Thus will he be able to re-order and re-form his environment. Fundamental to this task, Kepes states, is an understanding of the principles of structure. In his book, Structure in Art and Science, Kepes maintains that "in order to live freely and fully in our new world, we have to learn to map its strange vistas, to discern in them harmonious structures appreciable by our visual sensibilities . . ." (15:i). To relate successfully to the environment, Kepes believes that as well as pursuing knowledge to its farthest extent, man must also "combine and intercommunicate all such knowledge so that we may gain the sense of structure, the power to see our world as an interconnected whole: (15:ii). And if one considers the relationship of vision at this point, Kepes says that "the most powerful imaginative vision is structure-oriented" (15:ii).

One finds structure as the basis of all organization. Kepes traces it from the complex spiral molecule of DNA, to the Gestalt psychological theory that our perceptive processes are determined by well-defined networks of sensation based on structural laws and through man's expression in art and architecture. In fact, he considers contemporary architecture and engineering as the "most impressive manifestation" (15:iii) of our interest in structural principles.

Engineer Pier Luigi Nervi and architect Mario Salvadori have both observed that the "ever-increasing size of contemporary buildings has brought the problem of structure to the forefront" (15:iii). Salvadori sees that, along with the population explosion, society has been providing more and more services. Man requires and is given

> . . . more schooling, more travel, more medical care, more entertainment. The mass media allow and compel large numbers of people to gather under the same roof for all the gregarious activities so typical of our era. Large stations, large stadia, large theaters, large churches, large arenas appear in increasing numbers. Urban agglomerations require the sprouting of taller buildings. The large structure has become a symbol of our culture . . . (24:6).

If man as a population has affected structural design, he also has been affected by it. In his book Architectural Environment and Our Mental Health, Clifford B. Moller writes that man's structured environment is an important influence on the shaping of personality. He points out that in this age of urbanization the man-made environment has come to represent more and more of the total environment for most people. He then adds that "too often our existing urban habitat is taken for granted, treated as inevitable and as if nothing could be done about it" (21:90). Moller is concerned that although in the next ten years man may build more buildings than have accumulated since the beginning of civilization, he may sacrifice the quality of architectural design and spatial planning for the quantity demanded. It is Moller's contention that there is often excessive attention paid to the form a building takes rather than to the effect of the spaces--that the visible aspects of design are more easily comprehended than the intangible ones. He also states, rightly, that the total architectural environment must transcend the merely visual, or structural. He believes that if the designer's main efforts are directed toward creating form, then spatial needs are often neglected; "form should be only a by-product of the ultimate goal in design . . . [the] meaningful interaction between man and his environment" (21:130). Nonetheless, he is in agreement with Kepes when he writes that the total architectural environment must be aimed at the creation of a sense of order, [or structure]. Although the physical structures that form space are static, it is the form or structure that initiates the design process and makes possible the varying uses of space. Structure can be the basis of exciting and dynamic spaces, that also fill man's needs.

In Structure Systems, Heinrich Engel agrees with Moller that architectural design should have as its goal the resolution of the conflict of man and his environment. He is also able to relate the significance of structure to the larger whole of the design solution (total environmental design) and sees structure as one component of design, among other factors such as historical continuity, regional and site conditions, and psychological needs of society. Engel sees structure (much as Moller) as being the instrument for humanizing space:

> Only through structure can space be spanned, so that the life of individual, family, or society can unfold; through structure space can be controlled so that man can safely live, move and work; through structure this space can be enriched, be given scale and aesthetic quality.
>
> . . . .
>
> The purpose of structure is to serve the physical and spiritual being of man. Its merit is solely measured on how well it does this job (10:20-21).

A final consideration of the influence of structure on architectural design must include the use of building materials. Talbot Hamlin in the book Forms and Functions of Twentieth Century Architecture has developed a criteria for judging the use of materials into two categories: one dealing with the use of materials as affected by their essential nature, and the second dealing with their use as affected by their function. What is significant in the structure-material relationship is that materials often determine the expression of the structural form and that the physical structure itself will often dictate nature of materials that is important--for example, some materials are better suited for covering long spans than others; in other cases, a highly rigid or highly flexible material might be required structurally (13).

If structure is such a significant part of the design criteria, it obviously seems important for the designer to be conversant with basic structural principles. Salvadori writes of the relationship between the architect and the engineer, which could be interchanged with architect and interior designer. He writes that "the contemporary architect, perhaps the last humanist of our time, must be conversant with aesthetics, engineering, sociology, economics, and generally with planning. Instead, under the influence of tradition, he is often trained primarily as an artist" (31:7).

On the other hand, the interior designer is trained in space planning, in the behavioral influences of space on individuals, and often in aesthetics, sociology, economics, and planning. A dialogue between architect and designer often is nearly impossible, since, as Salvadori states, they lack in some areas, a common vocabulary (31). In Building for Modern Man, Severud has suggested that there needs to be more consideration and communication between those with common design goals: "Certain basic principles occur and reoccur throughout all aspects of the provision of the proper physical environment for man. If those fundamental principles could be mastered by all the designing professions alike, they would serve to link them together in a mutual understanding . . ." (6:114).

Purpose

Many schools and universities offer courses in history of architecture and architectural aesthetics, but courses dealing with structure and structural systems have usually been available only at schools of architecture, and these are often too complex to suit the needs of the designer and layman. It is the purpose of this paper to make available to the interior designer and layman an introduction to the vocabulary of structure and building materials and their interaction, and to present this information with an accompanying visual presentation.

Definitions

Because the area of structure uses a certain technical vocabulary, the following definitions of terms will serve as a reference to the concepts discussed in the review of literature and analysis of the slides. The sources of these definitions are Building Structures Primer, by James E. Ambrose; Architecture: A Book of Projects for Young Adults, by Forrest Wilson; and An Historical Outline of Architectural Science, by Henry J. Cowan. The theory of the structure is not generally discussed at this point, and many of the definitions--especially those dealing with structural principles--will be described in greater detail in the review of literature and analysis of the slides.

Arch. A structural form, taking the shape of a curve, which can carry an imposed load across an opening, to supports. It resists compressive forces.

Bay. The segment of space defined by a pair of roof trusses of transverse vaulting; or the space between girders in a framed floor; or the space between two interior pillars or columns.

Beam. A structural element used horizontally and resting upon two or more supports. The beam carries transverse loading and in resisting this loading develops internal forces of bending and shear. A beam may be freely supported, that is resting evenly on two supports at the end of the beam; it may be "cantilevered," or cantilevered eqully on both ends over two supports; it may be "continuous," or spanning several supports; or it may be "fixed," or set into two supports instead of resting upon them.

Bearing Wall. A wall which acts as a major supportive element in a structure. It is generally massive and capable of carrying great loads.

Bending. A force which causes a curve or sag in a straight element. It is characterized by the opposition of the internal stresses of tension and compression.

Bending Moment. A reaction brought about by loads acting on the structure.

Buckling. A failure or collapse of a structural member subjected to the force of compression. It takes the form of a sudden sidways deflection or movement, and occurs at right angles to the direction of the load on the member. It may occur if the compression member is too long and slender for the load it carries.

Cantilever. A structural member that projects out and is supported only at one end, or the part of a beam which overhangs its support.

Catenary. The natural curve or form taken by a cable hanging under its own weight, between two supports.

Column. An upright member which is subject to the force of compression; generally cylindrical in shape, although it may also be square; H-shaped when made of steel; in the form of a cruciform or cross; scalloped; or used with several other semi-circular columns to form a cluster.

Component. A single part of a larger system. A structural member such as a beam is considered a component of the whole structural system.

Compression. One of the primary forces that acts on a structural member. It has the tendency to shorten the member by crushing the particles together.

Connection. The union of two or more structural elements. It may also be called "joining," referring to the actual connecting element that unites two or more separate members. The actions of members on each other may often be seen in the action on their joining.

Construction. The process of building; the uniting of various members and forms.

Curtain Wall. A thin wall between structural members or hung from a skeleton frame, which carries no load.

Dead Load or Weight. Sum of the weight of the various members of the structure themselves; also any fixed load. It is separate from the added load or weight of external forces like the wind or internal weight, such as furniture.

Deflection. The movement of a structural member, under pressure, away from its original shape. An example would be the bending of a loaded beam.

Deformation. A change of shape and size in a structure, caused by forces acting on the structure.

Determinate. Referring to a structure with defined limits. The structure has the exact sufficiency of stability both externally and internally, and can be determined by consideration of the resolution of force alone. If there is an excess of stability, the process of calculating the stability is called indeterminate.

Dome. A structural element that can be considered as a series of arches revolving about a central axis. It takes a convex shape and generally hemispherical form.

Dynamic Load. Any load that causes motion, such as an earthquake.

Elastic. The ability of a structural member to return to its original shape after a load causing deformation is removed.

Equilibrium. A quality of balance; when a system of forces equal each other and prevent movement or change; for example, a downward force equals an upward force.

Failure. Loss of capability; inability to continue functioning. Failure may affect only a specific member, in which case the loads are rerouted; or it may affect an entire structural system, because of collapse of a crucial member, such as a bearing wall.

Flexible. Not stiff; capability of being modified.

Flexure. Bending.

Form. The shape; the shape of the structural members or parts, and the overall shape of the whole structure (the sum of the parts).

Force. An effort; something which exerts motion or pressure on a structure or structural member. The tendency of a force is to either move the structure or member, or change its shape. A force has magnitude (weight), direction and location. External forces, such as wind and snow, act on the structure, as well as internal forces, such as compression and tension in a beam.

Fracture. Breaking; especially occurs in tensile failure.

Framing. The "skeleton," the timber work of a structure - floors, roofs, partitions, beams; or in steel construction, columns, beams, and girders.

Hinge. A joint that allows free rotation of the members it connects.

Hoop Force. Internal, horizontal force inherent in a dome.

Hyperbolic Paraboloid. A double curved or parabolic surface, formed by straight lines; often has a saddle shape.

Indeterminate. Incapable of specific determination or uncertain; the opposite of determinate, in structural analysis.

Lateral Support. A support from the side. A diagonal support that makes a structure more rigid is an example of a lateral support.

Lintel. Often used interchangeably with "beam" as in "post-and-lintel." A horizontal member, usually short-span, over a door or window.

Live Load. A load that can be moved. An added force or weight not inherent in the structure itself, such as furniture, or the wind.

Load. An applied and/or external force that acts on a structure; for example, the forces caused by gravity, wind, or snow.

Load-Bearing Wall. Another term for a bearing wall.

Member. A part of the structural whole.

Membrane Structure. A tension member that has no bending or compression forces.

Moment. A term which expresses a force times the distance at which it acts. It is an action which causes rotation. For example, a bending moment causes a curve or sag in a beam.

Monolithic. An element that is cast in one piece; such as a concrete slab.

Motion. Movement resulting in a changed position. Rotation is the motion of turning.

Post. A vertical structural member that acts in a supportive manner.

Post-and-Beam. A structural system of a horizontal beam resting on two or more vertical supports or posts.

Pre-stressed Concrete. Concrete reinforced by adding a pre-tensioned steel cable either before or after the concrete has been molded and hardened. It allows the concrete to be more resistant to tensile forces.

Reaction. A response or responding force. A supporting structure responds or reacts to its loads.

Redundant. An excess of members, rigid joints or reactions which make a structural indeterminate.

Reinforced Concrete. Concrete strengthened by adding steel bars, rods or mesh; produced by pouring the concrete over the steel, which is not stressed mechanically after the concrete hardens, nor is it prestressed.

Rigid Frame. A frame having rigid or fixed joints. A rigid joint allows no rotation of the members it joins and keeps a right angle under a load.

Rotation. A turning motion.

Shear. A force that causes a separation; caused by two parallel forces or loads that act in different directions, and results in two parts sliding away from each other.

Shell. A thin and curved structural form.

Space Frame. A system of trusses developed in a three dimensional manner; very rigid.

Stable. Able to remain in a fixed position; having sufficient support.

Static. Motionless or at rest; an equilibrium of forces.

Static Load. A load which does not cause any sudden change or motion.

Stiffness. The ability of a structure or material to resist deforming.

Strain. A change in shape or deformation due to stress.

Stress. An internal resistance produced by an external force. Tension, compression, and shear are the three major types of stress.

Structure. A system of members, such as posts-and-beams that resists deformation by various forces.

Tension. A force that acts on a member and produces a stretching or lengthening; a pulling apart.

Thrust. A twisting force.

Truss. A rigid framework of tension and compression members in triangular form; very stable.

Vault. An arched roof.

CHAPTER II

REVIEW OF LITERATURE

Many different approaches appear in the literature about structure: some authors view structure from the side of statics, mechanics, and engineering design, while others are more concerned with the philosophy and aesthetics of structures themselves. Presented here are several main topics with discussion of the approach toward them taken by different authors.

1. An introduction to structure and the meaning of structure in building.

2. Physical principles that determine structural design.

3. Use of building materials.

4. Major structural systems.

5. Possible future developments and ideas concerning structural systems and materials.

An Introduction to Structure and the Meaning of Structure in Building

Nearly every author who has written a book dealing with the subject of structure has in the first few pages made the statement that structure is the essential component of architectural design. It is difficult to imagine enclosed space without some basic system that makes the enclosure possible. A building cannot exist without some underlying or supporting structural system. Ambrose defines structure as "that which gives form to something and works to resist changes in the form due to the action of various forces" (2:6). In addition, he states that structure may be considered as inseparable from the object, as an eggshell or a canvas tent is; or it may be distinct and separate; as in the case of the human skeleton.

Other authors have defined structure by its functions, or what it should do. William Zuk indicates that "in simple terms, the purpose of a structure is to hold a building up" (40:7). More exactly, a structure must withstand all the forces that act on it and transmit them to base supports. Salvadori relates that structure has served to satisfy not only man's physical needs for shelter since earliest time, but has also served as a natural expression of man's innate sense of beauty (31).

Edwardo Torroja, a brilliant engineer, architect, and innovative designer, summarizes the primary functions of all structure as:

1. Enclosing space by walls and roofs, and protecting it from not only the natural elements like rain, but also from thermal changes and noise.

2. Providing passages for movement by ways of bridges, floors, stairs, and ramps.

3. Resisting lateral thrusts of earth or water, as a dam or reservoir must.

4. Resisting external and internal forces to maintain a state of equilibrium (38).

Heinrich Engel considers the function of structure and the design of structural systems from a more aesthetic point of view; stating that the primary reason for such systems is the creation of architectural form and space. He indicates that of all the component elements that contribute to material existence, whether it be a house, a tree, or human being, structure is the most essential element, because "without material structure, [there is] no organism, animate or inanimate" (10:19). Even though structure alone doesn't make architecture, it nonetheless makes architecture possible. Engel emphasizes an attitude of humanization through structural design. He states that the reality and meaning of architectural structure is seen in the purpose it fulfills: "to make possible material forms that serve the physical and spiritual being of man" (10:21), and that one must judge a structure's value only by how well it serves this function. One of his major tenets is that structure is fundamental to the creative design of architectural space, and that through structural design, architecture gains the ability to create humanized space. Structure is what makes possible the spanning of spaces for homes and human activities; it protects man and makes his survival easier; it enriches space and gives it a scale to which man can relate (10).

Going on from this point, Salvadori and Rosenthal stress that although structure is the beginning of design, it does not necessarily dictate the form of architecture. There are many examples of structural "wrongness" that have lasted through the ages as beautiful buildings. Salvadori cites the Parthenon as translating in marble structural forms (post-and-beam) that are typical of wood construction. The question of aesthetics enters in, more precisely, as the integrity of the structure and its form. He writes that correctness of structure is generally a condition of beauty, but that correctness of structure alone cannot guarantee beauty. Some engineers such as Pier Luigi Nervi design structures that are at once correct and beautiful, while other designers have used unusual building techniques, yet their structures cannot be called more than ordinary (31). Rosenthal believes that there is "a fundamental rightness in the structurally correct concept," and that it is an absence of structural correctness which is mainly the reason for the "prevailing lack of feeling the average layman experiences when faced with contemporary architecture" (30:2). An example of integrity in structural design which he refers to is the use of the concrete shell to span space in a more elegant, cleaner, and more direct way--with more "economy of means"--than posts, beams, and trusses.

William Zuk faces the question of "integrity" from a slightly different perspective. He disagrees with the idea that "a structure which is integral with the architectural form is of a purer nature than a structure whose form is concealed by other architectural features." His criterion for a good building is one of function combined with beauty, and he indicates that the controversy of structure-integrated-with-form is of little consequence. To support this, he refers to several natural examples; a tree with the structure completely exposed and itself the form; and in opposition, a gazelle with flesh and fur covering the skeletal structure. But he hastens to add that even if the structure is not seen, the general form it conveys is inescapable and unavoidable, and that a form alien to the structure would be as discernable as a cow's body on the gazelle's bone structure. There is, therefore, integrity of the structure, whether it is visible or not (40). Ambrose expresses his concern with the idea of structural "correctness" by stating that "what constitutes the correct structure is that alternative solution whose limitations come the least in conflict with the functional demands placed on the structure (2:5).

This leads to the final idea considered: the design criteria for structures. Ambrose suggests that the need and use of the structure should have priority, followed by location, orientation, size, shape, and cost determination. At this point, these goals are translated into structural terms; location may refer to factors such as the soil content, wind forces, building codes, and labor costs. Then the designer must consider problems of structural behavior, such as load-bearing capacity, and non-structural problems such as fire resistance and construction costs. Ambrose has arranged a thorough list of requirements for determining the way a building is developed. The designer must consider:

1. Form limits; the overall shape.

2. Scale limits; from lot size to room sizes.

3. Physical needs; resistance to wear and damage.

4. Structural needs; strength of materials and form, stiffness, etc.

5. Relation to building functions; movement, ventilation, acoustics, lighting, etc.

6. Special needs; mobility or permanence, or modifications (2).

After this, the designer may make his own evaluations about which of all the structural systems that may work will best express the use and feeling of the structure--whether the building is humble and modest or flamboyant and daring. Rosenthal does not detail the criteria as precisely, but again the idea is implicit that the architect must know "what is going to happen;" he must understand structural principles, choose the correct materials, determine the most expressive form. This is "building correctly" and "obeying" the building! The architect must know the underlying demands and design accordingly (30).

When Zuk speaks of structural criteria, he considers the definite jobs it must perform, the action of forces to be considered, the strength of materials and the form they are used in (for a structure could fail, even if made of strong materials, if they aren't correctly used), and the harmonious joining of different materials and elements, to prevent a clash of form and structure (40).

Torroja maintains that the ultimate purpose of the building must be the first problem considered. Then he must determine which materials are the most suitable and the economic considerations. These are often influenced by physical factors such as climate, topography, labor available, and transportation. Finally, but of equal importance, is the aesthetic quality--which will determine reaction to the building. All these factors must be integrated into the design criteria (38).

Heinrich Engel sees design as a creative synthesis--the resolution of the conflict of man and his environment. The approach taken must involve total environmental design, and the architect must be both generalist and specialist--knowledgeable in economics and sociology, engineering and art, planning and design. Today's designer, however, cannot be expected to fully measure and exploit every facet of building that technology has made possible. There are engineers who are structural specialists; those who specialize in one area of structure such as reinforced concrete structures; others who are even more specialized, in designing only reinforced concrete roofs. The architect has become a member of a team of specialists who collaborate on design; he bears the burden of collecting the data and expressing it beautifully. Engel sees all design criteria as the instruments for humanizing the total environment. But he stresses that in order to judge and develop this ability, one must be well-versed in the physical nature of structure and forces and be able to make knowledgeable, scientific evaluations (10).

Finally, one may state that structure and form are generally interdependent and a design criteria must be developed before any building goes beyond the imaginary stage. Consideration is given to need and function of the structure, forces and loads, strength of materials, site factors, construction costs, and the expression of the form, or how the building will look.

Physical Principles that Determine Structural Design

Nearly every text considering structural design will focus on the principles that will determine what form the structure may take. Although the actual calculations and engineering involved in designing a building are outside the scope of this paper, it is important to understand what forces act on structures and how they are resisted. Salvadori has concluded that the principles of structural action can be understood by an intelligent layman untrained in higher mathematics or physics. He also adds that once these basic principles of structural analysis are defined, one does not have to be a specialist to begin to understand structural behavior. In fact, everyone has some familiarity with the way structures act in his own life: one sets a ladder at the correct angle to carry his weight, or knows whether a plank over a stream will support him as he crosses. From this intuitive recognition of general architectural situations, it is an easy step to systemize the knowledge and to begin to understand how and why a structure works (31).

A building which is standing has many forces acting on it--both externally and internally--which it must resist if the building is to stand for any length of time or be safe to use. The fundamental problem in design is then to have a state of balance existing in the structure, which is commonly defined as equilibrium. This is such an important factor of design that nearly all the authors cited in this paper begin with a discussion of equilibrium.

Equilibrium is defined by Salvadori as a condition which guarantees a building will not move (31). Parker defines it in terms of forces acting on a structure: that these forces must be constantly in a state of equilibrium (or the building will move) (26). Ambrose agrees that when there is a balance of forces, that state called equilibrium exists. A static equilibrium exists when a created force is resisted by an equal and opposite force. Structures receive forces and transfer them to other areas. Reacting forces which develop at the points of transfer are combined with the applied forces to become a set of forces that acts on the structure. This set of forces has to maintain equilibrium, or movement occurs. While the structure must be able to resist external forces, it must also be able to resist forces that occur internally, or again the building will change shape or move. This internal equilibrium depends on the structure's internal stability and strength. Failure may occur if these conditions aren't met--a thin sheet of aluminum may crumple, or a framework joined with loose pins may collapse, indicating a lack of internal equilibrium, or stability and strength (2).

Equilibrium depends on the separate balances of both external forces and internal forces. Applied external forces must be opposed by externally sufficient reaction condition; internally, there must be sufficient strength and stability to transfer applied loads.

Zuk takes a very straightforward approach to the concept of equilibrium when he states that the vertical and horizontal forces acting on a structure must be resisted by exactly the same of vertical and horizontal forces within the structure and what supports it. He adds, it could also mean the downward forces acting on a beam are resisted by equal upward forces; or the external applied forces acting on a small part of the beam are countered exactly by internal resisting forces in that part of the beam (40).

Torroja writes that equilibrium involves not just immobility of the whole structure, but also of its members and their connections. Again, he brings out the concept of equilibrium as a state of balance produced when the parts of the structure and their connections are combined so that at the supports there are produced reactions which balance the applied forces. This includes the force created by the structure's own weight (38).

The next logical consideration is to define forces and how they act in determining equilibrium.

Corkill asserts that a force exerts motion or tension or compression, and that whether or not a structure is in the state of equilibrium depends on the resolution of these forces (4). Parker says that a force tends to change the state of rest or motion of a structure. The force may push or pull at a definite point and in a definite direction. This tends to cause motion, but the motion may be stopped by opposing forces. A force is determined by its magnitude, direction, line of action and point of application (26).

Rosenthal sees force in an even different way, and describes it as arrested movement. He indicates that "force" tends to be an abstract conception, and it really isn't able to be visualized until it is met by a resistance. A car parked on a hill is subject to the force of gravity; the brakes act as the resisting force. There is equilibrium, and no effects are seen unless the brakes are released (30).

The ultimate state of equilibrium occurs when one force is resisted by an equal and opposite force both acting along the same line. But this state occurs only infrequently in actual buildings--as when a load acts concentrically on a column, or in a cable. When this state does occur, of a force equilibriated along a direct path, the material is used most efficiently. Usually, however, short and direct paths of forces and reactions (or equilibriants) take place only in individual members, not the structure as a whole. Buildings are to enclose space, and when this happens, all forces are deviated. But for the most economical effort, all forces should come down to earth in the most direct way possible. "Detours" of forces cost more in structural economy. It exemplifies an old fundamental rule of geometry; the shortest distance between two points is a straight line. In structure, the shortest distance would be the straightest path the forces could follow. Rosenthal carries this reasoning further by adding that the less deviation there is from this direct path to equilibrium, the smaller would be the forces involved (30).

In further analyzing forces, Corkill classifies them into live and dead loads, imposed primarily by the force of gravity. Live loads can be applied to, or taken away from the structure. Examples are loads resulting from wind, snow, human beings, or furniture. Dead loads are forces inherent in the structure, such as its weight. These are permanent loads (4). These dead loads and other vertical loads, as Salvadori writes, are generally resisted by suitable structural systems. Wind loads, a type of live load, often require a form of diagonal bracing added to the structure. Horizontal bracings are seen beneath bridges, while vertical bracings are usually hidden within walls of buildings (31).

But in discussing forces it is not enough to define them as live or dead loads. It is also very important to make a distinction between static forces and dynamic forces. Ambrose and Salvadori both consider a static force to be one that does not move or change, or else changes very slowly. The force of gravity acting on a structure is a static force. A dynamic force or load is one that depends on motion, or is applied quickly or changes rapidly. Vibrations from earthquakes, or the effects of people walking in a building are examples of dynamic loads (2, 31).

The effects of these forces are quite different. A light steel frame structure may strongly resist static forces, and yet vibrations from a dynamic force may cause cracked plaster and a general feeling of instability to the occupants. On the other hand, a heavy stone or brick building may not be as strong statically as the steel frame one, yet will absorb easily the energy of dynamic forces because it is still and heavy (2). Salvadori chooses a different type of example: if a nail is hit quite hard by a hammer, the result is different than if the weight of a hammer is slowly applied to the nail. The effects of a dynamic load are often as much as 100 percent larger than its effects would be if static (31).

Ambrose writes that forces are characterized by the way they are dispersed on the structure. The weight of water on a flat tank and the weight of snow on a flat roof are loads that are uniformly distributed on the surface. The weight of a beam can be said to be uniformly distributed on a straight line. At the base of a column, however, the load is concentrated in a comparatively small area (2). Parker also discusses concentrated loads and uniformly distributed loads. He cites a girder resting on a column as a concentrated load; and a wall supported by a beam as a uniformly distributed load (26).

Ambrose, Zuk, Salvadori, and Engel give some consideration to the main sources of force that will affect structural design. Ambrose classifies some important sources as:

1. Gravity: the weight of the structure itself; of its contents and occupants; of snow and ice or water on roofs; generally a downward and static force.

2. Wind: moving air; a horizontal force, calculated as a static force.

3. Earthquake: internal earth fault which causes tremors; a dynamic up-and-down or back-and-forth force.

4. Thermal expansion and contraction: materials shrink or swell due to fluctuation in internal and external temperatures; distortions may occur within the structure (2).

Salvadori adds that thermal changes may dictate some aspects of structural design. When a structure has to carry heavy loads and small temperature changes, it can be made very stiff. On the other hand, if it must withstand great temperature changes and relatively small loads, it has to be made flexible to allow for changes. The structure is resisting thermal loads in this case by "giving" (31).

Other factors related by Ambrose that may cause problems in structural design are shrinkage forces in certain materials; handling forces created in transportation and handling; forces caused by settlement, warping, or slippage of structural connections; and vibrations from machinery or high-volume noise (2).

Both live and dead loads cause forces and stresses within the structure. But before examining the major types of forces and reactions, it is important to understand the relationship of forces, stresses, and the structure itself. Forces which act on a structure produce internal action within the structural members, or stress. Parker calls stress an internal resistance which balances an internal force (26). Corkill defines stress as caused by internal forces acting with a structural member. Stress can also be seen as a force per unit area. Corkill also gives examples of how stress may be visualized; snowshoes can be used for walking over deep snow because they spread the stress of the weight of the person walking on the snow over a fairly large area; a high heel of a woman's shoe, on the other hand, concentrates a large stress in a small area. He draws the conclusion that when the load is widely distributed, the force of stress will not be as great. Also, when light loads are concentrated in a small area, they may produce great stresses (4).

Ambrose relates that internal forces occur within a structure through which the structure resists a change of shape caused by external forces. The measurement of force is described in weight units and is called stress. Internal forces are always joined with deformation of the material, called strain (2). Rosenthal states that any given stress produces a strain that can be observed (30). Parker adds that a force acting on a structural member causes a change in shape or volume, called deformation, and that strain is synonymous with deformation (26). Ambrose continues this evaluation by writing that a structure subjected to a force will twist, curve, stretch, shorten, sag; or technically speaking, it stresses and strains. While a stress is not usually seen, its accompanying result, strain, is often seen. If a person stands on a board which rests between two supports, his weight will cause the board to sag or bend. The sag is the visible manifestation (or strain) of a particular stress--the weight of the person on the board. Stress and strain are interdependent (2). Stress is significant structurally, according to Corkill, because if there is an internal force acting in a structural member which produces a stress greater than the material can resist, then structural failure results (4).

Corkill concludes that both live and dead loads cause forces and stresses within the structure. He lists these forces as compression, tension, shear, torque, and bending (4). Parker and Torroja, on the other hand, state that the most frequently occurring internal forces (stresses) are tension, compression, and shear, with torque and bending being various combinations of these three main stresses (26,38).

Ambrose explains that compression, tension, and shear are all forces that cause movement in a particular direction or along a certain line; other forces cause rotation--a force that causes twisting is called torsion or torque, while an action that causes curvature is called bending. Tension and compression, Ambrose indicates, are the easiest forces to visualize because one is the opposite of the other (2). Compression is the force that tends to condense matter, it is a pushing or crushing force. Corkill further describes compression as the forces that push against an element and make the material more compact. A pile of stones is an example of natural compression. The weight of the top stones cause compression in the lower ones (4). According to Rosenthal, in a situation of direct compression, all forces are directly opposite their reactions (30). Compressive forces can be transferred without a connection through simple contact bearing (2).

Compression may cause two different types of failure--crushing and buckling. The phenomenon of buckling is particularly common with compressive stresses. For example, a slender column shortens when a compressive force is applied at the top. A basic natural law demands that a physical phenomenon will follow the "easiest" choice of paths. It is easier for the column to shorten (or crush) for small loads and to bend out or buckle for large loads. For strength against buckling and to be efficient, compression members cannot be extremely slender, and yet should use as little mass as is possible. A round, hollow cylinder or an I-beam, fulfill this requirement in especially good ways. Salvadori also adds that structural elements which develop the stress of compression are quite common, because eventually all loads must be channeled down to earth (31).

Tension can be described as a force that tends to cause a pulling or stretching apart of matter (4, 1). Tension is caused, according to Corkill, by the application of opposing external forces. A spider descending causes a pulling (and thus a tension) on its supporting thread. Suspension bridges are common man-made examples which use tensile forces

(4). Tension may require the use of certain materials, such as steel, and the connections between members are often more difficult to achieve in a state of tension than in one of compression. Tensile forces tend to cause a tearing at holes in structural members; they tend to straighten crooked elements; and they require a connection for the transfer of forces (2). Rosenthal adds that the use of tensile materials in building has made possible the bridging of wide spans. When forces are directed along tensile lines with a minimum of detours (or without setting up moments) then light, elegant structures can be created (30).

According to Corkill, shear is a force that may divide an element along a plane parallel with opposing external forces (4). Salvadori calls shear a type of stress that causes particles of the material to slide relative to each other (31). Ambrose states that a shear stress causes slippage in two adjacent points in a structure (2). A shear stress may operate either horizontally or vertically (26). This concept is not difficult to understand if it is illustrated. Corkill refers to an overhanging ledge on the side of a cliff, which may succomb to shear forces and break away (4). Salvadori cites an example of a paper punch, which uses shear in punching out holes in paper; also rivets in connections are susceptible to the stress of shear. A cantilevered beam built into a wall may shear off along the wall (31).

Salvadori states that one characteristic of shear is that it causes sliding along two planes which are always at right angles to each other. Shearing stress has a tendency to cause rotation in a member; this leads to a complex relationship in which shearing in vertical planes necessarily involves shearing in horizontal planes. Shear also involves tensile and compressive forces, and this is of importance in building materials. A material low in tensile strength will also have little shear resistance (31).

Both Salvadori and Corkill define torque, or torsion, as a force which is produced by twisting and which may cause shear strains and stresses (31, 4). Ambrose also writes that torsion, like bending, is a product of force times distance (2). The effects of torsion depend on the shape of the structural member, its length, and how it is supported. A round, hollow cylinder is considered the most effective shape for resisting torsion. Any twisting motion of the body, states Corkill, is an example of the force of torque, or torsion (4).

Bending, the final force discussed, may be described as the result of a pair of opposed forces (2). Corkill indicates that bending causes deflection by inducing tension and compression (4). Ambrose and Salvadori relate the way bending occurs: in a plank or beam or other straight member, the top develops compressive stresses while the bottom develops tensile ones. The result is seen as a sag and is called bending. Ambrose maintains that if the tensile and compressive forces can be held constant, then if they are widely separated in a member, the more work the member can produce. A plank turned on its broad side can span less than half the distance of one turned on its edge (2). Salvadori also relates that one of the fundamental structural problems is to transfer vertical loads horizontally when spanning a distance between supports. Bending can be considered as a means of channeling vertical forces in a horizontal direction (31).

The forces of compression, tension, shear, bending, and torsion may occur in any number of combinations and in several directions at a given point in the structure; the combined stresses often become quite complex (2).

Another principle that must be evaluated in structural design is a moment. A moment is a force which acts through distance (4). Corkill explains that if a man holding a brick holds it close to his shoulder, the force of the brick or its moment is much less than if he holds it with his arm outstretched. If the distance the force must travel is considered as a lever arm, then to find the moment, one simply multiplies the force times the distance or lever arm. If one speaks of moment in a beam, the principle is the same. If a 20 foot beam has a load of 10,000 pounds centered on it, the moment at the center of the beam can be found by multiplying the end reaction (5,000 pounds) times the lever arm (10 feet); the moment is 50,000 foot-pounds. The beam must resist this moment internally (4).

Corkill also writes that as the external moment is reduced, the internal resisting moment within the beam is reduced. The external and internal moments must be equal if the beam is to resist the applied load. Also, the depth of beams becomes significant in considering internal forces. A shallow beam carries larger forces, while a deep beam carries much smaller ones, and less material is needed to resist internal forces. This phenomenon is evident in a quite ordinary situation. If a flat piece of paper is held at one end, it bends quite easily under its own weight; the internal lever arm is small. However, if the paper is shaped into a curve, it will not bend because the lever arm of the resisting moment is large enough to equal the applied or bending moment (4).

Finally, in determining the principles of structural design, there are certain other general factors that are of concern. Torroja and Parker both mention resistance as significant. Torroja writes that the material of all parts of the structure must be able to resist all the internal forces that are created by loading, plus the action of the external forces (38). Parker sees resistance as the ability to avoid deflection, and states that it is determined by stiffness and strength of the members. Understanding how a structure is deformed under loads aids not only in knowing the state of stress in the structure, but also where and how a member may fail. Resistance may be said to be the material's capacity to avoid failure and it is necessary for sound structural design (28).

Failure is not the only danger a structure is susceptible to (38). Instability may affect the whole structure or individual members. Any structure which carries loads has certain requirements, Structurally, it must be stable. Salvadori indicates that stability pertains to avoiding unacceptable motions of the building as a whole (31). Exterior stability can be obtained by attaching the members rigidly to each other or by bracing the structure (2). Rotational instability, or the whole structure toppling over, may occur if the building isn't set properly into the ground, or if it is supported on soil of uneven resistance. Piles may be driven deep into the soil to rest the building on, insuring stability; or in water-logged soil, the building "floats" on the soil by means of a raft-type foundation (31).

Closely related to stability is the requirement of strength. According to Salvadori, strength is concerned with the integrity of the structural system under loading (31). Ambrose relates that a structure may be stable, but not strong. Strength, he says, is determined by the type of material used, and the way in which it is used. A plank made of steel can carry more weight than a wooden one. The strength of materials is determined by the types of stress involved. Steel can remain strong in tension, compression, twisting, or shearing. Wood may be made strong by laminating it. Masonry materials are well able to resist compression, but are very weak in tension (2).

Rigidity is not synonymous with strength. Two buildings, states Salvadori, may be equally safe, even if one deflects more under loading (31). Ambrose writes that all structures move or change shape under loading. The material and design of the structure as well as the applied forces will determine how much, and in what way, the structure deflects. Rigid structures usually move less than flexible ones when they are loaded. Rigidity may depend on the material itself or the way it is shaped. Steel is more rigid than wood, and an I-beam will bend less than a flat one (2). Salvadori cautions, however, that rigidity can be a drawback in structures that must endure temperature changes, uneven ground settlements, or dynamic forces and loads (31).

In conclusion, it becomes evident that structural design is a process of balance between imposed forces and the way the forces are resisted. A structure must carry any number of varying forces. The designer must understand the forces at work and distribute them in accord with what Zuk calls the scientific "law of least work." The creative designer must seek to ease stresses and distribute forces evenly. Zuk writes that "badly designed buildings show their wounds with sags and cracks" (40:14).

Use of Materials

The strength of a structure and its capacity to resist loads are determined somewhat by the choice of building material used. Each of the common structural materials has certain unique characteristics that make it suitable for particular structural uses. Often times, the choice of material also expresses the feeling of the structure, through a certain texture or color or feeling of mass. Although each material has a different design capacity, there are certain essential properties that all share in making them able to resist loads.

Salvadori considers the problem of deformation as a primary factor in choosing structural materials. When loads act on a structure, the deformation that naturally occurs must not increase indefinitely, and should disappear after the action of the load ends. Thus, a material in which deformation disappears quickly after removing loads behaves elastically, and all materials are elastic to a certain degree. Also, most structural materials are linearly elastic within definite limits; that is, deformation is proportionate to the load--a beam having a deflection of one-tenth inch under a ten ton load, has a two-tenth inch deflection under a twenty ton load. Materials which keep a permanent deformation, even after the load is removed, behave plastically. All materials have a yield point, after which deformation becomes permanent, and failure may occur. In ordinary construction, then, materials should behave elastically (31).

Materials can also be classed by the types of stresses they can resist--primarily tension, compression, and shear (31). While all materials can resist compressive forces, some cannot resist tensile forces; those that do not work well in tension are generally also weak in resisting shear stresses. It becomes very important in structural design to know at what point the material yields to deformation or fails under loading, in order to make a building safe for use, or to know how much overloading a building can take before it collapses (31).

Structural materials generally in use are wood, masonry, steel, aluminum, reinforced concrete, and plastics.

Wood. Wood has the unique characteristic of being the only living or organic building material in wide use in construction. However, this uniqueness is also its limiting factor in construction use. From the day it is cut, it begins dying and as it ages its usefulness as a structural material lessens (31). It is a much less permanent material than stone or concrete, although if the material is used properly it is sufficient for most building needs. Ambrose cites the houses of Cape Cod and Oriental temples as examples of wood structures that have endured over time (2). Generally, though, wood is used extensively for small-scale buildings and residences, or for scaffolding, bracing, and forming in construction, rather than for large-scale or multistory buildings.

Insects or fungi can affect wood, and it is by nature susceptible to changes in humidity which can cause swelling or shrinking and drying. Despite its structural limitations, wood has an aesthetic advantage over some other materials; its color, grain, and texture convey an attractiveness and feeling of life that make it highly pleasing to the eye. It is widely available and is fairly low in cost, so it has been a widely used material. Structural use is mainly limited to soft woods, among them Douglas fir, Southern yellow pine, Northern white pine, spruce, cedar, and redwood (2).

As for resistance, wood is much stronger in resisting stress at right angles to its grain than along it; splitting can occur along the grain (31). Torroja writes that wood is capable of resisting tension and compression equally in the direction of its grain. However, wood can fail in compression if a permanent load causes excessive deformation; this is usually a slow failure, often taking months to occur. Failure in tension can be much more abrupt than compressive failure, as when a beam breaks under excessive loading. Stresses in wood are often strongest at the points of connection, where the member may split or shear horizontally; also, changes in humidity may affect the connection, if the wood swells or shrinks (38).

New techniques in using wood have added to its structural possibilities; surface treatments may increase protection against insects and fungi, and preshrinking lumber adds to its resistance against humidity and connection stresses. But the most significant advancement has been the development of lamination, a process that bonds with glue several layers of wood and which greatly increases its structural capacities. Plywood is a widely used laminated wood in which the grain in each layer is at right angles to adjacent layers (23).

Masonry. This class of structural material includes brick, stone, and concrete blocks and is one of the oldest classes of building materials. Its common characteristic is a joining of each unit (such as a brick with another brick) by means of a bond, such as mortar (2).

Stone masonry, according to Torroja, is quite expensive and generally reserved for monumental-type buildings. If a good quality of stone is used, the building can stand practically forever. The use of stone is indicative of great mass, and this material is highly resistant to compression, but very weak in tension (38). Bearing walls, which are usually massive and heavy, characterize the type of structure that stone is suitable for.

Brick is a material which is a mixture of the four elements--air, earth, water, and fire. Brick, although it can be used massively like stone, has a different quality. The scale or size of each brick is generally smaller and standard in size. The richness of color and contrasting mortar make brick structures seem lighter and more intimate in feeling than stone structures. Varying textures and colors are available in bricks. The bonding element, usually mortar, is significant because it makes the brick structure much more resistant than if the bricks just rested on each other (38).

Like stone, brick is strong in resisting compressive forces but weak in tension. Some advances in reinforcement techniques which extend the structural possibilities have been made in recent years, but brick and stone construction is still generally limited to walls and piers. Structural drawbacks to the use of brick are the requirement of hand labor in laying the bricks, and the possible shrinkage of mortar and cracking due to thermal expansion (2).

Steel and Aluminum. Steel has the distinction of being considered not only the most versatile of structural materials but of having the most reliable quality due to its strength and ability to resist aging (2). Torroja states that steel has not been given an adequate expression of its inherent qualities, as stone, wood, or brick structures have. Except in engineered structures such as bridges, steel structure has been hidden behind alien facades. Torroja indicates that part of the reason for this is that steel is a fixed, inflexible material with none of the color or textural advantages of wood and brick; in fact, steel structures often have a skeletal look which seems to need covering up by a skin of other materials (38). On the other hand, an article in the September 1961 issue of Progressive Architecture describes steel as lending itself to a skeleton-type framework, and then indicates that often structures are designed to accent the steel frame (36).

The problem of connections is important in steel structures, as it was in wood ones. Rivets, when used, may be susceptible to shear forces, and complex patterns may develop around riveted areas. Welding permits connections not possible with rivets and allows a continuous flow of forces, so that the connection acts as an integral part of the structure, which allows a more efficient utilization of material and transmission of forces. Steel is light, strong, and ductile. Per unit volume, it has the highest stress capacity of commonly used construction materials. Steel is strong in resisting compression and tension. Because of its great strength, steel members can be made quite slender, and the refinement of steel cables has opened up a whole new concept of elegant and light tensile structures (38).

Although steel is valuable because of its strength and elasticity, it has two structural disadvantages. It gains heat rapidly and may loose strength in fire situations, and it oxidizes quite easily (38). Ambrose writes that new techniques such as coating the steel with noncombustible paints are reducing the fire hazards, and painting or weathering the steel protects against corrosion (2).

Aluminum is the other widely used metal in building. Generally, it is used in alloyed form and it can be used not only in nonstructural ways (such as curtain wall facades or roofing) but also in some structural capacities (2). Aluminum lends itself particularly well to use in light weight geodesic domes--one particularly notable example is the dome covering the St. Louis Botanical Gardens, in which the entire tubular framework of the dome is aluminum (36). Its chief structural advantages are its lightness and resistance to corrosion, while it is disadvantaged by low stiffness and low resistance to buckling (2).

Reinforced Concrete. While other types of concrete are used in construction, reinforced concrete is by far the most important. Concrete by itself is usually massive and heavy, excellent for resisting compressive forces, but extremely inadequate in resisting any kind of tensile forces. Torroja describes reinforced concrete as a material in which the reinforcing steel resists tension and the concrete resists compression, or "steel gives tenacity to stone and concrete gives mass to steel" (38:36). He describes reinforced concrete as the most nearly perfect material developed in its ability to resist stresses.

If concrete is to be used practically as a material for beams or girders, it must be made to resist tensile forces. When a beam is supported at each end, the beam tends to bend, with the upper portion of the beam compressing, while the lower portion elongates. To resist the tensile forces, steel rods or bars or meshes are added, unstressed, to the concrete while it is still soft. These are carefully placed in the part of the structural member where tensile forces occur (26). When the concrete sets or hardens, a fairly strong bond forms between the concrete and the steel. This type of concrete is called normal reinforced concrete, and while it is much stronger than ordinary concrete, it has one major drawback. When loads are applied to a normally reinforced concrete member, the steel acts with the concrete and cracking occurs (7).

Prestressed concrete is a second form of reinforced concrete which avoids the problem of cracking by replacing the ordinary steel reinforcement with highly stressed steel tendons (7). In the prestressing of concrete, tendons of extremely strong steel are stretched through the concrete and pulled against the whole concrete mass, which the tension of the tendons compresses. The "locked-in" stresses of an unloaded beam compress the concrete and tense the steel, and the concrete beam is never really in a state of tension (31). More simply, the stresses are placed in the member before it is ever loaded; so that loads placed on the beam produce no tensile forces. Prestressing is done by two methods: pre-tensioning and post-tensioning.

In pre-tensioning, the steel wires or tendons are stretched through an empty concrete form, and then hydraulic jacks pull or stretch them to a certain tensile stress; concrete is then poured in the frame and allowed to harden. When the jacks are released, the steel tries to shorten and the stress is transferred to the concrete; the concrete becomes "prestressed" or put under compression and causes locked-in tensile strength. Prestressed in this manner, the member has a slight arch upward (31).

In post-tensioning, the concrete is poured into a form or bed and allowed to harden through which channels are made for the passage of the steel wires. After the concrete sets, the tendons are slid through the member and anchored at one end. At the other end, a hydraulic jack tenses the tendons. When the jack is removed, the steel tendon is anchored, and the stresses are again transferred to the concrete. Post-tensioning is used for long spans or heavy loads (31).

One important advantage of reinforced concrete is its ability to be shaped to fit the variations of stress which occur in a structure. A significant disadvantage is its weight in a liquid state. Also, elaborate and expensive form work is often required when concrete is poured in place (17).

Plastics. Plastics could be considered by many as the material of this age; they certainly permeate nearly every area of our lives--plastic furniture, dishes, containers, signs . . .

In architecture, plastics have had a wide range of nonstructural uses, from floor, roof, and wall coverings, to insulations and piping. More recently, they have begun to be used in a structural manner, in load-bearing members or secondary members. Plastics are synthetic organic materials, based on carbon compounds, and capable of being re-formed by pressure or heat. There are between twenty and thirty different types of plastics, with an almost limitless number of subvariations or subspecies (8).

Dietz indicates that "plastics have no inherent form, but may be given desired shapes" (8:5), and that when plastics are reinforced, they can achieve great strength and resistance, while still remaining fairly light in weight. When used structurally, plastics which lack stiffness are often combined with glass fibers of exceptional strength to produce fiberglass reinforced plastic. The result is a light, strong material suitable for construction. Plastic coatings may also be laminated or sprayed on other surfaces (particularly tent structures and pneumatic structures) as a protective coating (8).

Problems occurring in the use of plastics are low stiffness, lack of resistance to fire, and fairly high costs (2), but new technological advances in the development of plastics should add exciting structural possibilities.

The concept of future possibilities of materials has been explored briefly by two authors. Zuk and Clark, in Kenetic Architecture, indicate that a high-strength-to-weight ratio may influence future trends and that heretofore unused materials such as paper, may be bonded or laminated to light metals or plastics to form a new type of material. Also, they believe that certain new exotic metals with high-strength-to-weight ratios will be much more extensively used. These include boron carbide, berillium, titanium, fiberglass, and other plastics (2).

On the other hand, Nurse warns that metals are becoming more expensive as ores are exhausted, and petroleum, which is the main source for plastics, is becoming more scarce. He encourages the further refinement of concrete, silicate materials, and glass-concrete combinations as future building materials; and he looks to these new inorganic materials as relieving some strain on environmental resources and being produced cheaply and easily (25).

Major Structural Systems

Buildings, generally speaking, are comprised of not just a single structural element, but a combination of many. Ambrose suggests that if one were analyzing structural systems, the following items should be considered:

1. How specific members function: some support in compression (columns), some support in tension (cables), some span (beams), some cantilever away from the body of the structure.

2. The geometry of the form and way the load is carried: an arch and a beam both are used for horizontal spans, yet their form is quite different. An arch and a cable also span horizontally, but they differ in the way they carry a load.

3. How structural elements are joined, since connections are important in transmitting forces.

4. The action of forces and loading conditions that will occur (2).

Just as a building can be composed of several structural systems, so the actual way a structural system is designed can occur in several different ways. The designer can begin with a specific material, exploring and exploiting its form possibilities, and then arrange these forms into a system. Or he can begin with a particular structural form like the arch or shell, develop it into a workable system, and then find the material which expresses the form best. Or he can begin with broad considerations of the function of the structure and the form and scale and then seek ways to form the system through specific structural elements and materials (2).

If there is to be an evaluation of a building, an understanding that includes how a building works as well as how it looks is desirable; if there is to be an appreciation of forms that beautifully express their functions, then a vocabulary of structural forms must be learned. Each structural element or form has specific qualities that make it suitable for some situations and unsuitable for others. Although there are different ways of classifying structural forms, the one most authors seem to prefer is classification by configuration or a particular means of construction. The following structural systems or elements will be considered: bearing wall, post-and-beam, truss, space frame, slab, arch, vault, dome, shell, tensile elements, and pneumatic elements.

Bearing Wall. A bearing wall is a structural system that distributes vertical compressive forces which are applied at the top of the wall, down to the foundation (38). A natural example occurs in some of the eroded rock formations found in Western United States (4).

Forces are transmitted vertically downward, and since the weight of the wall increases toward the base, equilibrium can be maintained (preventing the wall from overturning) by thickening it at the base (4). The bearing wall acts somewhat like a wide, narrow column. If the wall is not made thicker at the base, the stresses are not distributed to the ground over a wide area, and the load may exceed the soil's bearing capacity; to counteract this tendency, a footing can be added to the base of the wall, which distributes the stress over a larger area of soil (40).

For maximum efficiency, loads on a bearing wall should be uniformly distributed, and openings such as windows and doors should be framed properly, to avoid disturbing the structural continuity and potential of the bearing wall (2). If concentrated, widely-spaced loads occur, the forces of these loads are transmitted to the wall and may crush it, unless reinforcing is placed along these areas (such as pilasters), but then the bearing wall begins to take on the characteristics of the post-and-beam system (4).

Stability in a bearing wall may be obtained through adding buttresses, which is essentially adding mass. A more efficient means is to develop stability through geometry--that is, place the bearing wall at right angles to another bearing wall, or make it curved or serpentine in shape (4).

The bearing wall usually expresses massiveness and permanence; materials usually associated with this structural form are stone, brick, or reinforced concrete, which are essentially compressive materials (2).

In summary:

1. A bearing wall primarily resists compressive forces and utilizes compressive materials.

2. It does not span space, but is rather supportive in nature.

3. Uniform loading produces the most structural efficiency.

4. Stability is better obtained through positioning the form than adding mass.

Post-and-Beam. This type of structural system transmits loads horizontally by beam and vertically by posts. The beam element spans, while the posts act as supports. The beam must resist bending and shear forces, while the post must resist mainly compressive forces. The posts also may have to resist some horizontal loading, such as wind pressure. With this type of force, wood and steel may bend, but by sheer weight and mass, stone or brick piers can resist the force (31).

The post-and-beam system rarely occurs in nature, although examples of posts are tree trunks, blades of grass, and even the human leg (4).

If a load is concentrated at midspan of a beam, half the concentrated load is transferred horizontally to each support and then to the ground. If a load is distributed evenly along the whole beam instead of concentrated at one point, it is called a uniformly distributed load. Each support receives or carries half the load. If the structure is to remain in equilibrium, all the vertical forces acting downward must be equalled by the vertical resisting forces upward (4).

The post-and-beam system can be used as a multistory frame, in which one system is built on top of another. Logically, the columns below each system must support its own load, plus that above, so the lower columns will be larger than the upper ones (4). Vertical loads are carried well by this system, but horizontal loads are not (31).

There are several possible ways of utilizing beams. A simply supported beam is one which is supported at each end; however, the beam can rotate and expand or contract longitudinally. If a load is applied uniformly, Salvadori writes, half the load is transferred to each support, and the beam deflects and bends. Bending stresses in the uniformly loaded beam are maximum at the midspan, while shear stresses are maximum at the supports. In steel beams, compressive stresses are particularly high at midspan and twisting can occur. To minimize this action, triangular openings may be made along the center longitudinal strip of the beam (the neutral axis) which is never in a state of tension or compression. (In a "normal" bending situation, it will be recalled, the top portion of the beam is in a state of tension or compression, while the bottom is in a state of tension). These openings make the beam lighter, but the beam begins to take on characteristics of another system, the truss. Salvadori calls the uniformly loaded, simply-supported beam inefficient because of the bending stresses which occur at midspan (31).

The beam supports may be shifted toward the center of the beam, and the beam then has one or two cantilevered sections (31). That is, the one or both ends project outward over the supporting posts. Naturally occurring cantilevers are tree branches and cliff overhangs (4).

If a uniform load is placed on the part of a singly cantilvered beam <u>between</u> supports, then the cantilevered end tends to rise, and the beam bends in the midsection. However, if a load is placed on the cantilevered section of a beam, the beam tends to deform down at the cantilever and upwards toward the farthest support. The beam must be securely fixed at this point to prevent it from deflecting upwards. A uniformly loaded double cantilever (or a beam with cantilevers at each end), is usually more efficient than a uniformly loaded single cantilever. The efficiency is obtained because there are two cantilevers "balancing" each other and countering the internal forces of the central span. This makes possible an increased center span between two supports, without increasing the internal stresses. It is a more efficient use of the post and beam system and of materials (4).

If a uniformly distributed load occurs on a simply supported beam, internal stresses are large and the beam must be fairly deep. But Corkill states that if a uniformly distributed beam is doubly cantilevered over two supports, the area of the beam can be reduced to about one-third of that area of a simply supported beam. This is a clear example of the structural efficiency of the cantilever. Also, because the cantilevered beam may use less material, a lighter system, both structurally and visually, will result (4).

If the beam ends are fixed into a support, the beam becomes more rigid and rotation does not occur. In this situation, a beam can usually carry up to fifty percent more loading than a simply supported beam; also, the beam is nearly five times stiffer if the beam ends are fixed (31). Another way of producing stability in the post-and-beam system (especially lateral stability) is to attach the members rigidly. When all the joints are rigid, if one member is loaded transversely, the joints are capable of transferring bending among all the members (2). All members "share" the loading, and the rigid joinings give this system inherent stability.

Joints are highly important in rigid frames because the greatest stresses occur at these points. Steel is a particularly well suited material for the rigid frame. Joining occurs through rivets or welding, which allows the greatest monolithicity. Often steel rigid framework is braced by trussing or infilled walls to increase its stiffness. Reinforced concrete which is poured as one piece is naturally monolithic and rigid. If the structure is made from separately poured parts, extending the reinforcing will preserve the monolithic character (2).

A continuous beam extends over more than two supports and it has somewhat more resistance to concentrated loads than other beam types (31). Continuity in beams is useful where spans are long in relation to loads because deflection is reduced (38).

In summary:

1. The post-and-beam system utilizes horizontal beams which must resist bending, and vertical posts which must resist compression.
2. Beams may occur as simply support beams, as cantilevered beams, as rigidly attached in a rigid frame, or as a continuous beam.
3. Steel, wood, and reinforced concrete are widely used materials for this system.

Truss. A truss is a structural system that is a framework of relatively short, straight members arranged in triangular form. The members must resist direct tension and compression forces, but no bending forces (40). The truss occurs infrequently in nature but may be found in certain bird bone structure, as strength without excess weight or material is needed (4). It has been noted previously that a rectangular form by itself may be unstable laterally, and that this form could be stabilized by making it a rigid frame, or adding a diagonal brace, and making it a truss (2).

There is a multiplicity of joints in the truss system, and the triangle is the only geometric form which holds its shape if all the joints are hinged (39). The triangle is a very rigid and internally stable form; whereas a rectangle that is hinged at the joints (and is free to rotate) will collapse under loading (4).

Internal stresses on a truss are concentrated on short, rigid members, and tension and compression are the forces that must be resisted by the members. The tension members are more efficient than compressive ones, so a truss should have as many tension members as possible (40); the tension members of a truss can also be lighter, so the dead weight of the structure is reduced (39). However, in every truss system there must be at least one compressive member. In a truss, the structural efficiency is obtained through what Ambrose calls minimum mass and maximum separation (2).

Because of its inherent lightness, resistance to bending, rigidity, and stability, the truss is especially well suited to long spans. Trusses can also be used to form arches and rigid frames, reducing the weight of a solid structure (2).

One unique type of truss combines the rigid frame form with the truss principle. The Vierendeel or open-web truss is made up of a series of attached rigid frames. This type of truss eliminates the diagonal member and frees the use of that space (40); however, it is less economical than a triangle-based truss because it is more susceptible to deformations and deflections. This form is efficient in absorbing lateral forces and is frequently used in buildings that must resist strong wind loads (35).

Steel offers perhaps the greatest range of joinings and member forms in the truss system, but reinforced concrete is being used as well. In the latter instance, joining elements are eliminated since the members are cast as one piece. Although this type of truss would be very resistant to fire and deterioration, its weight would be a drawback (2).

Wood is also used in truss construction, but is not as strong as steel in tension.

In summary:

1. The truss is a triangular framework of short rigid members.
2. The members act in tension or compression; bending forces are eliminated.
3. The triangle is an inherently stable form, and the truss which uses the triangle form is also very stable.
4. The truss is light and rigid and resists bending, making it an excellent form for long spans.
5. The Vierendeel truss combines rigid frame and truss principles.
6. Materials that are used in trusses are steel, wood, and reinforced concrete.

Space Frame. This type of structural system utilizes intersecting trusses in a three dimensional system. Or, one might call the space frame a three dimensional truss. The space frame occurs naturally in bone structures (4). The triangle is the basic unit form, the structure is inherently rigid and stable; and as in the truss system, the primary forces developed are simple tension and compression. Two important elements of this system are the supports and the joinings.

If the support of a space frame is by simple piers or columns, the concentration of forces at these points would be very large, similar to those in a flat slab at support points. Large members would be required at these points. A lattice support which is a trussed form itself, becomes an integral part of the space frame, and creates a more gradual distribution of forces from the frame to the support (4).

The space frame system of two dimensional trusses is stiffer than a system of parallel trusses, and it can be made much shallower (31). Because of the lightness and rigidity, this system can be used for long spans.

Shapes other than the flat span are also available with the space frame. The lamella roof is a space frame designed on the principle of a skewed grid. The arched beams are not parallel to the rectangular base, but at angles to it. Stiffer, shorter beams which act as if they were fixed instead of simply supported, increase the load-carrying capacity up to fifty percent. The rigid connections of the lamella arches induces torsion in the arches, as well as compression and bending forces (31). The lamella system can be designed from wood, steel, or concrete. Nervi is especially known for this type of space frame.

While the lamella is a space frame whose surface curves in one direction only, the geodesic dome has a doubly curved surface which allows maximum rigidity (33). Again, the basic design unit is the triangle, utilized in a spherical plane; direct tension and compression are the forces that must be resisted (4).

The geodesic dome has the space frame characteristics of lightness and rigidity that make large spans possible. As with the flat-spanning space frame, connections in this system are very important in transmitting and resisting forces, and must be designed very carefully. Naturally, the cost of the connections weigh heavily in the overall building costs (2). If the geodesic form is to be stable, thrusts which occur at the base must be resisted (4). The materials used in this system have been primarily steel and aluminum. R. Buckminster Fuller has exploited the structural possibilities of the geodesic form and has particularly stressed its ability to be prefabricated, its ease of assembly, and that the efficiency of the dome (large spans with minimum weight) increases with its size. Possible drawbacks to this system are the difficulties in providing well-integrated openings, suitable design of interior spaces, and provisions for certain integral service systems (often this necessitates suspended ceilings). Because of the complexity of stresses at the connections, the geodesic dome (like the rigid frame) is considered to be statically indeterminate, when the forces are being analyzed. Exact calculations of all stress is not considered feasible, since there is such a multiplicity of factors (4).

In summary:

1. The space frame utilizes the truss in a two or three dimensional form.

2. The primary forces that develop are tension and compression.

3. Supports and connections are significant design factors in this system.

4. Long spans are possible because of lightness and rigidity.

5. The lamella roof is a curved space frame, designed on a skewed grid.

6. The geodesic dome is a spherical space frame which can also have large spans, and which can be prefabricated and easily assembled.

Slab. This type of structural system is generally monolithic in form and is capable of distributing loads and resisting forces in one or more directions. The slab is made with relatively shallow depth and is mostly used over a rectangular shape. Forces developed in the slab which it must resist are bending, shearing, and twisting or torsion (31). The slab occurs naturally in flat horizontal stones, and in the palm leaf, whose ribbing, which is similar to a folded slab, makes the leaf strong and able to be quite long, yet thin (4). The slab system is a fairly new structural development, and reinforced concrete which is capable of being cast in one piece has made this monolithic form possible (38).

The slab may be used in different structural designs, and the conditions of support may vary. The state of stress in the slab may depend on how it is supported. In one case, a slab may be supported on two edges and reinforced in one direction; this is called a one-way slab (forces are developed in only one direction). If a slab is supported on all four edges and reinforced in two directions, this is called a two-way slab, since the forces then occur in two directions (40). Obviously, in a two-way slab the pattern of stress becomes much more complex, since bending and deflection occur in the whole slab, omnidirectionally (38). If the slab design is examined, it becomes easier to understand this concept. Salvadori and Zuk relate the idea that a beam transmits a load only in one direction--longitudinally. A load which occurs on a one-way reinforced slab follows the same principle of distribution; the load is distributed from the slab (which acts as a series of girders) to the supports in a direction parallel to the reinforcing steel (4).

If the slab is supported on all four edges, with reinforcing in two directions, the applied load is distributed in two directions parallel to the reinforcing steel (4). In a two-way reinforced slab, the loads are distributed as if a series of joined longitudinal girders intersects a series of joined transverse girders, to form a network or grid over which the stresses of bending, shear, and torsion act (31). All the parts of the slab share the distribution of the forces, and since a precise calculation of the forces and stresses is quite difficult to compute, this structure is considered to be statically indeterminate (40). A two-way slab is usually thinner than a one-way slab because of the transfer of forces in two directions (4).

The conditions of support for a slab may vary; instead of edge support, the slab may be supported by posts or columns. In this case, stresses become quite complex and concentrated at the points of support, and heavy capitals or shear connections must be used with the column. This permits a wider, more gradual dispersal of forces at the support and helps the slab resist a "punching" shear where the column and slab connect (31).

The slab system is widely used in construction; its smooth surface is optimal for pipes, ducts, and lighting. Also, reinforced concrete slabs are easily poured (as well as being suited to the monolithic character of the slab system), and the slabs can be lifted into place on supports by a hydraulic jack. The structural efficiency of the slab system can be improved by using ribs along the paths of internal forces. This allows the slab to be extremely thin in all except the rib areas. If the ribs intersect, a "waffle" type grid of ribs results, which resists forces in two directions (31).

Another variation of the slab system, which reduces the tendency of bending is the folded plate (4). A folded plate consists of thin slabs placed diagonally or tilted against each other and joined. The appearance is similar to that of a folded paper fan. The folded plate system acts like a series of small slabs leaning at angles to each other, and joined at the top ridges and bottom valleys (39). If the slab is folded in the direction of the span, it acquires more stiffness than a flat slab, and can carry up to 100 times its own weight (33). The folded plate combines resistance to forces by acting like both a beam and a slab.

Forces which act in a direction perpendicular to the fold are similar to forces in a horizontal one-way slab, and if the distance or span between folds is too great, failure due to bending may occur. The similarity to load distribution in beams occurs when the slab loads are transferred longitudinally to the supports. Corkill states that each of the plates in the system could be described as a tilted beam, with the upper part of the plate in compression, and the lower part in tension. The strength of a folded plate depends on how thick the plates are, and the pitch of the folds--the more the pitch decreases, the more the folded plate acts like a slab and becomes less efficient. To prevent the folded plate from collapsing, a restraint at the end of the plates or points of support must be added. A tie rod or bearing wall or certain other transverse stiffeners may be used to prevent the thrust of the folded plate system from causing collapse (4).

In summary:

1. The slab system is one-piece or monolithic in form, and resists bending and shear stresses in one or more directions.

2. A slab may be supported on two or four edges or by a system of columns or posts.

3. The structural efficiency of the slab system can be improved by changing the geometry. The use of ribs and the folded plate make the slab more resistant to bending and shear forces.

4. A folded plate resists compressive and tensile forces and must be restrained at the ends to prevent collapse.

Arch. This structural system is a spanning system that must resist compressive forces with minimal bending. The arch occurs naturally in some rock erosions, and in parts of the human body, such as the arch of the foot and the rib cage (4). The arch form is one of the most graceful and pleasing of all structural forms, and perhaps this is a result of the efficiency of the form.

The ideal arch form, called a catenary, should provide a continuous compressive stress line in order to minimize bending (4). Torroja relates the arch to the column since both resist mainly compressive forces; he defines the arch as a shape which follows the pressure line of acting internal forces, and which resists compression and transmits loads to two supports through a curve (38).

The catenary form is the counterpart of the parabola. If a chain is held between two points, its forces will follow the natural law of the easiest path to follow, and the chain will form a natural pulling shape (39). Wilson describes the catenary as the parts taking the most efficient form of pulling against each other, while Corkill calls the catenary "a free hanging cable with uniform loads attached at equal intervals to its entire length . . ." (4:118). If the catenary curve is inverted, an arch is formed and the line of stress takes the same line as the curve of the arch--a beautifully efficient geometric form. The most efficient arch form built usually falls between a parabola and a catenary. If the arch system of spanning is compared to the post-and-beam, it becomes evident that the arch fulfills its functions most economically. A beam develops both internal compressive and tensile forces, and vertical reactions only as the forces move down the supports; an arch has all internal compressive forces, and uses a horizontal thrust plus a vertical reaction in channeling these forces to supports (2).

Certain forces, or thrusts, develop at the base of the arch which tend to make it spread and these must be resisted. The horizontal force of thrust may be resisted either by an internal tie rod which balances the force at one end support against that at the other, or by external buttressing at the points of support such as heavy abuttments (2). To minimize the thrust of the arch, the arch rise should be as high as is feasible, and the arch should be as light as possible (31).

There are several types of arches possible: the monolithic arch, the two-hinged arch, and the three-hinged arch. A monolithic arch is one continuous form rigidly connected to supports and subject to bending stresses. The two-hinged arch has a continuous arch form, but it is connected to the supports by pins or hinges so the ends can rotate if there are temperature fluctuations or if there is settlement at the supports (31). Hinging means the arch is more flexible and has fewer, if any, bending stresses. The three-hinged arch is actually an arch in two pieces which are hinged at the supports and the crown. Again, there is free rotation, so the arch may adjust to stress or load variations, and in this case, bending forces are eliminated (4).

If an arch is extended along its plane, it forms a vault; if it is rotated about its center, it forms a dome (35).

In summary:

1. An arch is a curved form that develops compressive forces.

2. The most efficient curve for an arch should resemble a catenary curve.

3. The arch must use either buttressing at the supports or a tie rod to stabilize the form against thrust.

4. The arch is a graceful element, capable of producing large unobstructed spans.

Vault. The vault is a structural form that can distribute its loads either by arch action alone to supports, or it can distribute them in a combination of slab and arch action. The cylinder shape of the vault has its natural counterparts in such things as grass stems and bamboos; in structure, the vault or so-called cylinder shell is a primary form of shell structures (33).

The traditional vault system may be considered as a series of arches side by side (2). The stresses developed within the vault are primarily compressive, and the vault must resist bending stresses caused by the weight of the vault and applied loads (4). A continuous thrust is developed at the base of the vault which requires heavy buttressing to counteract the tendency of the vault to spread apart.

The contemporary vaulting system, however, resists forces in a different manner. The catenary curve which determines the arch does not determine the cylindrical shell vault generally built today (33). In fact, to design it in such a manner would impair its strength as a structural form. According to Torroja, it took a long time to change the concept of the vault and consider the longitudinal lines that play such an important part in the way it distributes loads (38). The contemporary vault combines the longitudinal action of plates with the transverse action of the arch (35). There are basically two types of vaults in this system: the short barrel vault (or short cylinder shell) and the long barrel vault (or long cylinder shell).

In the short barrel vault, the direction of the curve coincides with the direction of the span (33). Loads are transferred as if by slab action to the supports, and at the supports vertical loads are carried to the ground by arch action (4). If a series of short shells are used together, stiffening ribs of laminated wood or concrete may be used for stability; these short shells are often used to roof wide, single story buildings (33).

The long barrel vault curves at right angles to its span, and may be analyzed in a manner similar to the folded plate (4). The long barrel vault may be considered as a series of longitudinal adjoining beams, arranged in a curved form. The forces are transferred longitudinally as if in beams to the supports, instead of transversely like a series of arches. There is a resistance to shear, because the longitudinal elements restrain each other from deforming and the carrying capacity is strengthened; also, the thin shell structure resists shear stresses by nature. Transverse stiffeners may increase the stability and preserve the shape of the long barrel vault (33). The long barrel vault is often used for industrial halls and exhibition buildings (35). Reinforced concrete or corrugated steel are often used for covering vault surfaces (2).

A groined vault is a traditional building form consisting of two intersecting vaults. A ribbed vault, which is a variation of the groined vault, transfers forces through the vaults to ribs, and then to the points of support. The ribbed vault system simplifies the problem of continuous thrust by directing the forces to the points of support. The rods may be used to resist the thrust (4).

In summary:

1. The traditional vault form develops primarily compressive forces and its load distribution may be analyzed as that of a series of adjacent arches.

2. The contemporary vault develops shear forces as well as bending stresses, and transfers its loads longitudinally as well as transversely.

3. The contemporary vault may be divided into the short barrel vault and the long barrel vault. The short barrel vault curves in the direction of its span, while the long barrel vault curves at right angles to the direction of its span.

Dome. The dome is a structural system based on the rotation of an arch around a central axis. While a cylinder takes the arch form in one direction, a dome is a doubly-curved form (33). The dome has been highly favored in classical architecture. Torroja calls it a "natural answer to a need for structure" because it is able to enclose a maximum space with a minimum volume, and no intermediate supports. The dome can be a light, strong, resistant structure which uses a minimum of material (38). The human skull is an example of a naturally occurring dome (4), as is the shell of the sea urchin.

A dome can be described in terms of the arch; yet with the revolution of the arch, another dimension is introduced. Most structural authors describe the dome as consisting of meridian elements (which travel up and down) and parallel elements (which are circumferential, traveling around the dome) (31).

The traditional dome is often made of masonry or brick. The dome develops compressive forces which are similar to those in the arch and must also be resisted in the same way; and if it is not restrained by tie rods or buttressing, the thrust at the base of the dome will cause it to spread. If a circumferential tie rod is used, forming a tension ring around the dome, massive buttressing is avoided, and the structure will be lighter (4).

The action of forces in a dome is to a large extent determined by the transitional line, and above this line the dome develops compressive stresses, while below it, tensile stresses are developed. The transitional line depends on the mass of the dome and the loads applied. Compressive forces in a dome follow the direction of the meridians, while tensile forces move along the parallels (4).

Siegel examines the manner in which the doubly curved surface helps maintain the stability of the form. An individual arch, taken as a segment from a dome will be hemispherical, as the dome usually is. This shape deviates from the ideal catenary shape of the arch, and if kept isolated would tend to bend--sagging at the crown and bulging at the sides. When it becomes part of a three dimensional system, the tendency to sag is resisted because all the arches thrust against each other to form a solid cap, and all the forces are compressive. In the lower section, the elements form a horizontal band which resists bulging (33). The dome because of its geometry is extremely stable, but reacts more favorably if it is uniformly loaded, than if a concentrated load is applied (4).

Contemporary thin shell structures have begun to replace the traditional masonry dome (4). These domes are usually made of reinforced concrete and can be as thin as two inches (35). They are extremely rigid and resist bending (because of their thinness in relation to their span); they are strong and stiff. Care must be taken with the supports at the edge of domes, so that forces that concentrate in these areas are distributed without disturbing the continuity of the thin shell (33).

In summary:

1. The dome is an arch rotated about its central axis.

2. It is capable of large spans with minimum material.

3. Compressive and tensile forces develop along the meridians and parallels.

4. The thrust at the base of the dome must be resisted by tie rods or buttressing to assure stability.

5. Contemporary thin shell domes are being used more than traditional domes of masonry or brick.

Shell. The shell is a structural form whose surface is singly or doubly curved and which transmits forces along the curved surface to supports (40). According to Salvadori, the shell form is a structure which is strong through shaping the material according to the loads carried (31). Just as the arch form is efficient because it allows forces to take the easiest (or most direct) path of flow in one direction, so the shell continues this principle, usually in a doubly-curved direction. Ambrose writes that the shell may be called a surface structure (2); that is to say the surface and the structure are one in resisting and transmitting forces.

The shell form is one that seems derived from natural forms. The egg, the nut shell, the sea shell, are all natural examples of shells that suggest the two properties that are associated with this form: rigidity and curvature (4).

These two characteristics of the shell form determine its structural uniqueness. The loads which the shell must transmit and resist are carried in the direction and curve of the surface (or tangentially to the surface). A factor of great significance in the load distribution of shell structures is the curvature and extreme thinness. The curve of the shell has a tendency to cause direct stresses of compression, tension, and shear, which are transmitted efficiently to supports because of the natural law of the "easiest path" for forces to follow. The thinness works with the curvature to make the shell resist bending; in fact, the shell should be as thin as is possible. This idea becomes clear if one examines a soap bubble, which behaves the same way as a shell. The bubble is extremely thin and the forces are developed along the surface; if the shell or bubble is thickened, forces are no longer developed only along the surface, and bending may occur. An ideal material for the shell form is reinforced concrete which can be formed in both a thin and curved shape. The concrete resists compressive forces while the reinforcing resists tension; shells can be made from 1 1/2" to 6" thick, with 3" being average. Prestressed concrete is especially well suited for shell construction because the pre-or-post-tensioning of the steel reinforcing results in a natural arch or curve upwards (40).

The shell can take a variety of design forms; the thin cylindrical shell (barrel vault) and shell of rotation (contemporary dome) have already been discussed. Another commonly designed shell form is the hyperbolic paraboloid. This saddle-shaped form occurs when horizontal and vertical parabolas intersect and are "hung" between two upright parabolas (33). The hyperbolic paraboloid can also be visualized as straight lines arranged in a skewed manner between two end parabolas (4). The hyperbolic paraboloid is a popular shell design because it is comparatively easy to design and it creates an interesting warped surface (33).

Problems that occur in shell design are:

1. Keeping the shell form uniformly thin and avoiding abrupt thickening which causes disturbances in the stress pattern; this often occurs at the edges of shells, where they meet the supports.

2. The applied load should be uniformly distributed; concentrated loads cause excessive stress and deforming. An eggshell is strong if the force is applied over the whole surface, but concentrating the force in one area causes it to break.

3. Forms for pouring the reinforced concrete shell are often quite difficult to develop. However, the use of a concrete gun, which sprays layers of concrete on the reinforcing bars is helping alleviate this problem.

4. Various non-structural problems may develop such as acoustical problems if the shell is large and smooth and hard, and this may create lighting and insulation difficulties.

5. The mathematics of shell design is exceedingly complex (2).

The shell is an aesthetically exciting form, capable of covering large spans with open internal space, and is structurally very efficient if designed properly.

In summary:

1. The shell structure is a singly or doubly curved surface and is characterized by its curve and its rigidity.

2. Loads are distributed along the surface and in the direction of the curvature (tangentially).

3. The shell must be designed as thin as possible, to maintain its ability to resist stress directly and avoid bending moment.

4. Reinforced concrete is an ideal material for the shell form, allowing it to be thin, curved, and rigid.

5. Loads should be uniformly distributed throughout the surface and not concentrated.

Tensile Structures. If the compressive arch form is inverted, then the inverted arch becomes a tension form. The principal characteristic of tension is a pulling or stretching, and the tension member follows the line of its stresses (10). In a tensile structure, loads are distributed through cables or membranes to supports, and the system is designed to transmit tension forces. Tension structures occur naturally in spider webs, in bat's wings, and in the webbing of a duck's foot (4).

The cable is the major element of this structural system; it is a flexible tension member which may consist of one or more wires or ropes of high-tensile strength steel (steel is a logical choice because of its high resistance to tensile forces) (35). The cable transmits external forces through the simple stress of tension (10). The cable may be considered as flexible, because it has a small lateral dimension in relation to its length (31). The cable is capable of great spans.

The shape of the cable forms depends largely upon the loads applied and the stresses that result within the cable. The internal tensile forces resulting from the load are transmitted by the cables to supports; the supports transmit the forces in a compressive manner, so the conclusion may be made that a tension system requires compressive supports (4). The shape of a cable is governed by the load it bears, and the ideal tensile shape of a cable is called a parabola.

It is achieved by the shape a curve assumes when equal loads are horizontally spaced along the cable (31). The parabola is to tension as the catenary is to the arch. The structure will function most efficiently if the cable curve assumes a shape as close to a parabola as possible. The cable which is draped between two supports develops a horizontal thrust in the same manner as the arch (4). The less sag or slope there is in the cable, the greater the horizontal thrust will be at the supports and therefore, the larger the supports must be (2).

The cable changes shape under loading, so it always tries to assume the ideal curve for each load (10). This flexibility is considered a structural drawback, because stability is an inherent part of a structure. There are means, however, of stabilizing the cable, as well as reducing its susceptibility to wind uplift and flutter. Dead loads may be applied to the structure to increase the weight by structural members or ties which stress the cables and hold them in place (4). Or, the cable may be stiffened through construction means and made into a rigid inverted arch. Or, the cable may be spread against a cable with an opposite curve. Or, finally, the cable may be stabilized by adding transverse cables, anchored to the ground or a substructure (4).

Cables may be draped across single perpendicular spines, as in most suspension bridges, or across inclined supports, as in structures using the hyperbolic arch as end supports. The cables act as tensile members and the supports act in compression. Or the cable may be used in a system with tension and compression rings. This type of roof structure is similar to a bicycle wheel; the "spokes" are cables tensioned between an inner tension ring and an outer compressive rim, where the thrust is resolved and vertical loads are transferred to the group (31). This is a very stable system, with minimum flutter because pre-stressed cables are used (4).

The saddle-shaped or hyperbolic paraboloid roof follows the principle of mutually opposed cables, which cross each other and are anchored in inclined parabolic arches (33). This is also a stable form.

Tents are another form that may be considered as tension structures. The tent fabric can be considered as an extension of the cable, since fabric is really made up of a fine mesh. Siegel states that in no other type of construction as the tent does the form "flow so spontaneously from the structural principle." The form of the tent is itself the structure. The forces that act on the tent are resolved and distributed through the surface of the tent to the supports (33).

Tents are made of stressed fabric (or membrane) and to increase the stability and prevent fluttering, the tent structure can be secured by ties and guy wires or by forming a doubly-curved surface either by a specially cut fabric or from an elastic type of material (4). The supportive compressive masts, arches, or ribs are essential to the tent structure; otherwise it has no shape (33). The problem of increasing the stability is not the only one which occurs in the tensile structure. Up to now, there has been an inability to prefabricate the system, and construction costs have been quite high.

A membrane or fabric may be structurally sounder if it is tensioned before it is loaded. An umbrella is an example of a tent shape with "locked in" stresses. The steel ribs tension the cloth and give it shape when the umbrella is opened. Pretensioned membranes are stiffer and more stable than unstressed ones and do not flutter as easily as unstressed ones (31).

In summary:

1. A tension structure distributes loads by tension through cables and membranes to supports, which transfer the loads compressively to the ground.

2. The cable is a flexible member and tends to change shape under loading.

3. External anchoring, lateral cables, additional dead weight, or mutually opposed cables counteract the tendency of the cable to change shape.

4. Large, unobstructed spans are possible with tensile structures.

5. The cable may be draped or extended in different ways between supports.

6. A tent is a tensile membrane structure which acts in the same way as the cable system.

7. High construction costs, instability, and lack of prefabrication are drawbacks to this system.

Pneumatic Structures. The pneumatic structure is made up of a membrane which transmits tensile forces to supports and is stretched and supported by pressurized air. The pneumatically-stretched-skin is a structural system whose potential is just now being recognized. Up to this point, the pneumatic structure has been conceived of as a temporary structure or one relegated to unimportant architectural tasks. New concepts of designing with this form are being developed, such as multistory pneumatic structures (35). A soap bubble is the closest example of a naturally occurring pneumatic structure.

Stability in the system is developed through the differing internal and external pressures. The air is actually the main load-bearing element and the stretched skin of the membrane serves to transfer the force caused by the difference in air pressure to supports. The membrane is primarily needed to maintain the difference in pressure internally and externally (4). Air pressure is maintained mechanically and airlocks are the means of entrance into the structure.

Basically, there are two types of pneumatic structures:

1. An air supported single skin which may be compared to an inflated balloon. The system would fail if the skin is punctured, but the loss in pressure, unlike a balloon, would be very slow, so that occupants would not be endangered (2). Little material is used, but the structure is quite flexible.

2. A double membrane air structure has two layers of the skin, with pressurized air between them as well as in the building interior. The obvious advantage is that failure of one part of the structure doesn't necessarily mean collapse of the entire structure (4).

If both membranes fail, the action of escaping air is still gradual and would not cause any danger to people in the structure.

Most air supported structures constructed so far have been spherical or combining the sphere and half-cylinder (35), but any variety of shapes and arrangements is possible. Also, it is possible to vary the shape by the use of ropes and cables across the membrane. Not only does this provide surface variety, it reduces the membrane stress by collecting the forces and transferring them to supports through the cables (4). Another use of the pneumatic structure has been to give shape to other structures. Salvadori has used the pneumatic structure to support a reinforced form which is then sprayed with concrete; the pneumatic structure is deflated and taken out through the door (4).

This indicates an obvious advantage of the pneumatically stressed skin--it is easily portable. Additionally, it uses a minimum of material to provide a long, uninterrupted span. Certain disadvantages include the need for pressurizing systems and thermal changes which may require extensive cooling systems; also, more research is needed in developing an inexpensive, highly fire resistant membrane such as the one used on the United States Pavillion at Expo '70 in Japan.

In summary:

1. A pneumatic structure is a membrane which is stretched by air pressure which is greater inside than out.

2. The membrane is a separating element and transmits tensile forces to supports.

3. The pneumatic structure may have a single or double membrane.

4. The structure is light, portable, and uses minimal material for large spans.

Possible Future Developments and Ideas Concerning Structural Systems and Materials

Perhaps one of the most revealing comments about the trends in building came from a report to the American Institute of Architects on Creating the Human Environment: In the building industry, the real changes have not come from designs or materials, but from changes in the process of building. The building has come to be thought of, to a large extent, as a manufacturing process, from prefabrication, on-the-site construction, to precast elements (19).

Industrialized building includes such related functions as prefabricated buildings and parts, a modular coordination which lends a uniform size to standard building units, component standardized systems of building which include drop-in core utilities, and machine produced details evident in our buildings (2).

Along with new construction techniques will come certain new materials and products that may evolve into wide use. The A.I.A. report lists among them: chemically prestressed concrete, epoxy extrusion foams, plastic pressure piping, high-strength mortar, and plastic coated hardboard (19). Engel indicates that the development of fiberglass reinforced plastic materials has opened up a new world of structural design, and that the use of composite structures (or combining materials with different load-carrying characteristics into one structural member) will bring a combination of many unusal new materials (10). Engel cites designing structures as a continuum as one of the most remarkable new design ideas. Instead of each member having a single isolated task to perform, the continuum unites all the members and uses each as a multidirectional load-carrying element of the overall structure. This type of idea, states Engel, makes even new structural systems like the space frame and the shell seem isolated and old-fashioned (10).

Zuk and Clark present another attitude toward architectural design. They write that architecture is at the threshold of a new evolution, and reject the idea that to be successful architecture must endure. It is their contention that a highly refined form which allows flexibility to meet changing cultural needs is a better solution than a form which is inflexible but permanent. Zuk and Clark explore the kinetic response of man and his environment and have related some interesting architectural implications:

1. The significance of new materials will be determined extensively by a high-strength-to-weight ratio, and new materials that have emerged from the space program will be used.

2. The use of high-strength material often makes structures more flexible and vibration-prone; a kinetic response to this problem is to introduce stressing tendons into the structure that can be variably and automatically tensioned by mechanical sensors which "feel" movement and hydraulic jacks to control deflection. For example, if an object is dropped into an outstretched hand, the eye will detect the deflection of

the arm and will "instruct" the brain to send out responses to bring the arm back to level; kinetic control of structural deformation would be controlled in the same manner.

3. Structures can be developed to be self-erecting. The ideal building could come in a compact package, and energy input would develop it into a stable expanded form. A new nickel alloy produced by Goodyear seems to foretell this type of structure; the material has a memory that makes it capable of returning to its original configuration when heated, regardless of how it has been shaped. Pneumatic structures and self-erecting cable structures are also possibilities of this general type.

4. Architecture that can be added to, taken away from, or plugged into other forms may allow a new attitude toward impermanence in structural design.

5. Architecure that is short-term may be developed out of materials like cardboard or paper laminated with plastics and aluminum. It is the thought of Clark and Zuk that these developments will change the concept of what architecture should "do" and provide a new sense of aesthetics by letting people experience architecure by moving around and through it. It will be a response to changes in culture and allow more individual choice in one's personal surroundings; it will be an architecture in which the individual can become part of the process (41).

Another new trend is the use of computers in setting up data banks for information on design processes. Negroponte states that computers may be used to automate current building procedures and reduce costs, and that the designer and the computer can be trained to work together as a team. An interesting example is the use of the computer to perform graphically a design system and several alternatives from which the designer may select the one he feels is most appropriate (22).

Cowan sees environmental design as replacing structure as the fundamental problem of architecture. Since long spans and complex shapes are no longer difficult, then perhaps the structure of future building may be "distinguished by the elegantly restrained use of the appropriate system . . ." (5). The report developed by McCue and others seems to bear this out by stating that there is a necessity for a design team of engineers, interior designers, sociologists, etc., with the architect as the coordinator and catalyst, that will view the problem of design from a larger perspective (19).

However, there must be a knowledge of available possibilities and structural alternatives. Each member of this design team should at least be familiar with the language of structure. The report asserts that people do care about and are intensely affected by bad design or inattention to design. However, especially in the areas of design and construction, they have no vocabulary in common for expressing these concerns. The interior designer is part of the design team and is trained in the behavioral aspects of design; to communicate ideas to the other members of the team, it would be wise to at least be familiar with their language.

CHAPTER III

PROCEDURE

For the layman and interior design student who has had little or no exposure to the concepts of structure, the use of visual illustrative material is almost essential. The use of slides and film seemed a more flexible solution than simply illustrating the written material, a method which so many texts on structures have already utilized.

Much encouragement in this project came from several statements in Building for Modern Man. Severud suggests that dramatizing the essence of a structure through film can result in a more accurate conception than mere words and definitions, and can create a more lasting impression. Arnaud, in the same book, deplores the fact that most schools carry the use of visual materials no further than slides for a history of art or architecture course. He, too, believes that the contemporary designer can benefit from film and slides in a way that written material alone can never satisfy.

The use of slides for this project was determined as the most economically feasible method for an in-depth presentation of structural concepts. A film clip was developed to supplement the slides in a more general manner, and to show how a simple animated film could be created to be used in conjunction with slides in an introductory or summary role, or as an alternative method of presentation. A local architect was consulted to check the accuracy of the written material.

Development of Film

Although the writer had never made a film, much less an animated one, it was felt that animation could convey principles and concepts better than live-action film. After the script for the film was written, the type of animation was chosen. Cell animation (the standard type associated with cartoons) was discarded because of the tremendous number of drawings required, and the fact that it necessitates using an animation stand and camera for good quality animation. In addition, the cost for this type of film would have been prohibitive for the amateur film maker, and equipment necessary for it was not available locally. A cut-paper form of animation was chosen as being the simplest and easiest to photograph. The figures were made with moveable arms and legs, so that the film would have motion; faces and features were drawn on both sides of the figures, so that they could be turned over to change directions. The background and sets were made from Color-aid paper, for the same reasons as it was used for the slides. Also, the flatness of the cut-out sets was emphasized by the bright flatness of the paper. Thus, the illusion of depth or planes was eliminated, since the figures could only move back and forth. Rather than limiting the film, eliminating distances and depth seemed to enhance the final visual product, and the result was a freer, less conventional use of color and design.

Super 8mm color film was selected over 16mm film because the cost was considerably less. Also, Super 8 cameras were more generally available and simpler to use. A local camera shop loaned a Fujica Single 8 Z-2 movie camera for the project. The important consideration in selecting this camera was its capacity for single-frame exposure, which is essential in film animation. The camera used only Fujica Single 8 movie film cartridges and the processing was prepaid.

The camera was mounted on a tripod, and turned to face the subject being photographed, which was mounted on a board and laid flat on the floor. A cable release was used to trip the shutter. [Lighting was achieved by placing two 3400K bulbs in reflector units at 45° angles to that which was being photographed.] The writer, through experimenting, found the various number of frames necessary to expose in order to achieve motion in the figures. For example, to execute one normal speed step, two frames were exposed with the figure's legs completely closed; two more with them slightly opened; two more, wider apart; two more, with the legs at their widest; two more frames as the legs began to close; and two more as they closed--approximately twelve frames exposed for one step. The frame exposure could be increased or decreased to speed up or slow down the movements. One had to determine the total amount of time each section of the film should take and convert this to the number of frames used, which were individually exposed. For 50 feet of film, nearly 3700 individual exposures were made. It was necessary to keep the lighting the same for the whole filming process, because any change in lighting would change the quality of the color and be particularly noticeable after the film was edited.

Development of Slides

First, a written description of what each slide should illustrate was selected from the areas covered in the review of literature and put together as a shortened, separate and readable form. The slides of actual buildings and structures were either taken by the writer or obtained from personal sources, architects, or publishers of architectural books. The slides which illustrate theories or concepts were made from Color-aid paper on white or colored backgrounds. This type of paper was selected because the colors are bright and clear, which causes them to photograph more vividly than sketches or drawings. Another reason for using this paper is the flat or matte quality of its surface, which tends to reduce problems of glare with the lighting. Also, a wide range of bright, uniform colors could be utilized to present stronger color contrasts and cleaner looking forms than water color, pen and ink, or felt-tip pens.

The camera used for all the slide photography was a Minolta SRT 101 with 35mm, 58mm, and 135mm lenses. Also, for certain close-up slides, the Minolta Extension tube set was used. Film for outdoor photography was High Speed Ectachrome (Daylight-type) and for indoor photography, High Speed Ectachrome (Tungsten-type) was used. The indoor slides were taken by mounting the picture to be photographed on an easel approximately two feet from the camera's lens. The distance was varied, if necessary, to eliminate any border around the picture itself. The camera was mounted on a tripod, and a cable release was used to trip the shutter. Lighting was obtained by using two reflector units at 45° angles to the picture to be photographed, and bulbs with a rating of 3200K were used, since with this type bulb the tungsten film did not require the use of a filter.

CHAPTER IV

FILM AND SLIDE PRESENTATION

Film Presentation

The film clip is designed as a more general introduction to structural systems and materials. It may be of special interest to younger audiences, or those who have had little contact with the principles and materials of architectural structure. It makes use of simple animation to present some fundamental ideas about structural systems and their main characteristics, as well as the major building materials in use.

The film clip is not intended as a complete film in itself. It is to be used either as an introduction to the more in-depth analysis of structure and materials covered by the slides, or as an illustration of how film may be used, in a simple manner, to present abstract or complex ideas.

Slide Presentation

Slides 1, 2, 3. Man's environment is being destroyed--this news reaches him from every direction--his air, his water, and his land are in serious trouble.

Slides 4, 5, 6. At the same time, man is now the victim of his own visual pollution: endless highways, chaotic cities, billboards blotting out the landscape.

Slide 7. It is possible to say that things in our man-made world no longer reveal their character.

Slide 8. And our cities and buildings are without visual integrity.

Slide 9. Man responds to the physical world around him and develops his creative capacities from encountering it.

Slide 10. And at the same time he shapes his environment.

Slides 11, 12. To relate successfully to his environment, man must gain a sense of structure as the basis of all organization, from the simplest form of nature,

Slide 13. to super skyscrapers.

Slide 14. Man has come to live more and more in his urban surroundings, and he has begun to accept its disorder as inevitable.

Slide 15. The ultimate goal of design should be to reconcile man and his environment. Structure initiates the design process.

Slides 16, 17. Structure can be the basis of exciting and dynamic spaces that also fill man's needs.

Slide 18. Structure gives scale to the space man moves in, and spans space for man's activities.

Slides 19, 20. A designer today may be part of a design team that stresses environmental design, and the designer should understand the fundamental principles of structure, to communicate with the architect and engineer.

I. Introduction to Structure

Slide 21. A building cannot exist without some underlying or supporting structural system. Structure gives form.

Slide 22. The structure may be inseparable from the form, such as a seashell,

<u>Slide 23</u>. or it may be distinct and separate, like the human skeleton which is hidden by the body.

<u>Slide 24</u>. Structure can be said to: (1) enclose space by walls and roofs and protect man from the elements;

<u>Slide 25</u>. (2) provide passages for movement; and

<u>Slide 26</u>. (3) resist internal and external forces and maintain a state of equilibrium.

<u>Slide 27</u>. Structure is the beginning of design, but does not have to dictate form.

<u>Slide 28</u>. Some architects design structures that are both correct and beautiful, while others never seem to rise above the ordinary.

<u>Slides 29, 30</u>. Structure whose form is concealed is not necessarily incorrect, but there should be an integrity of form and structure.

<u>Slide 31</u>. A post-and-beam system should not try to look like a shell system, or the other way around.

<u>Slide 32</u>. Each structural system is "correct" as long as it meets its functional requirements with integrity.

<u>Slide 33</u>. A design criteria can be developed for structures: first must be considered the need and use of the structure;

<u>Slide 34</u>. then the location and orientation;

<u>Slides 35, 36</u>. size and shape, materials and costs.

<u>Slide 37</u>. Also, there may be special needs, such as making a structure mobile, that should be considered.

II. Principles

Slide 38. It is important to know the principles of structural action, and these can be understood without advanced mathematics or physics. Once these basics are defined, one does not have to be a specialist to understand structural behavior.

Slide 39. Everyone is familiar with the way structures act in his life; a ladder must be set at a correct angle to carry the weight of a person standing on it. This is an intuitive recognition of general architectural situations, and from here it is an easy step to understanding how and why a structure works.

Slide 40. A building which is standing has many forces acting on it, both internally and externally. The building must resist these forces if it is to remain standing or be safe to use. The fundamental problem is to have a state of balance, or equilibrium, in the structure.

Slide 41. Equilibrium exists when a created force is resisted by an equal and opposite force.

Slide 42. Structures receive forces and transfer them to other areas; reacting forces develop at the point of transfer, and must balance with the applied forces.

Slide 43. If the external forces aren't resisted, failure may occur. A force exerts motion, tension, or compression, and may cause movement or change in a structure, called deflection.

Slide 44. The simplest state of equilibrium occurs when one force is resisted by an equal or opposite force along a straight line;

Slide 45. as in the case of a column transmitting forces along a straight line, but this rarely happens in a building.

Slide 46. Buildings which enclose space transmit forces horizontally and vertically in "detours." The less detouring there is from the direct path of forces to equilibrium, the more efficient is the structure.

Slides 47, 48. Forces may be classified into live and dead loads. Live loads can be added to or taken away from the structure--examples are wind, human beings, furniture. Live loads such as wind, may require a form of diagonal bracing added to the structure.

Slide 49. Dead loads are forces inherent in the structure, such as its own weight. These are permanent loads. There are also static and dynamic forces or loads. A static force is one that acts slowly, like the force of gravity, while a dynamic force depends on motion or quick change, such as vibrations from an earthquake. These forces affect structures differently. The effects of a dynamic force can have a much more severe effect than if that force were applied as a static force.

Slides 50, 51. Forces may be characterized by the way they are dispersed on a structure. A uniformly distributed force is spread evenly over an area, while a concentrated force acts in a small area. Forces act on a structure and produce internal action within the structural member called stress. If an external load or force is widely distributed, the internal force of stress will not be as great as when it is concentrated in a small area.

Slide 52. Internal forces cause a structural member to change shape. This internal deformation is called strain, and while one often cannot see stress, one may frequently see its resulting strain. A structure which is subjected to a force will shorten, stretch, slide, twist, and curve. Both live and dead loads cause forces and stresses. The main forces that occur are: compression, tension, shear, torque or torsion, and bending.

Slide 53. Compression is easy to understand. It is pushing or crushing force that tends to condense matter.

Slide 54. A pile of stones is an example of naturally occurring compression, where the weight of the top stones cause compression in the lower ones. In direct compression, all the forces are directly opposite their reactions.

Slide 55. Compression may cause crushing or buckling failure. If a compressive force is applied at the top of a column, the force will follow the natural law of following the easiest choice of paths. A column will shorten or crush for small loads, and buckle for large ones. Compressive forces are common, since all forces must eventually be channeled down to earth.

Slide 56. Tension is a force that causes a pulling or stretching apart of matter. Tension may require the use of certain materials such as steel and connections are more difficult to achieve.

Slide 57. Tensile forces cause tearing at holes in structural members; they straighten crooked elements, and they require a connection to transfer forces.

Slide 58. Shear is a force that causes particles of a material to slide relative to each other.

Slide 59. A shear stress may occur horizontally or vertically, and cantilevered members may be particularly susceptible to shearing off along the wall.

Slides 60, 61. Torque or torsion is a force that causes twisting and as a result, shear strains. The effects of torsion depend on the shape of the structural member, its length, and how it is supported. A round hollow cylinder resists torsion best.

Slide 62. Bending is a force which causes a curve or sag.

Slide 63. It is the result of both tension and compression in a member. Compression develops in the top and tension in the lower part. Separating the forces makes less bending occur and means that the member can produce more work. Bending can be considered a result of channeling vertical forces in a horizontal direction.

Slide 64. Forces do not always act directly on a structural member. If a force acts over a distance, then a moment is created. Moment is fairly easy to calculate: the distance the force travels is multiplied times the force.

Slide 65. In structural design, resistance of the structure is also important. Resistance is the ability to avoid deflection under loading. If a structure is unstable, it may move under loading. Stability can be obtained by bracing the structure; joining its parts rigidly, or setting the structure on piles or a floating foundation.

Slide 66. Strength of a structure is determined by the type of material and how it is used. For example, stone is very strong in compression but weak in tension.

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III. Use of Materials and Major Structural Systems

Slides 67, 68. Each material has a different design capacity, but all materials share certain common structural requirements. For example, a material behaves elastically if its deformation disappears quickly after its load is removed. Materials which keep their deformation after the load is removed behave plastically. In ordinary construction, materials should be elastic. Structural materials mainly in use are wood, masonry, steel, and aluminum and plastics.

Slides 69, 70. Wood is the only organic material used in building on a large scale. However, after it is cut, it begins dying and as it ages, it is less useful.

Slides 71, 72, 73, 74, 75. It is a less permanent material than stone or concrete. Wood is used mainly for small scale or residential buildings, or for bracing and forming in construction. Insects and humidity may affect wood.

Slides 76, 77. But, despite its structural limitations, the color, grain, and texture of wood make it a highly pleasing material.

Slides 78, 79. Soft woods are mainly used for building, and the Southern yellow pine is the wood used most extensively. Besides its shortcomings as a living material, wood may split along the grain, or fail abruptly in tension.

Slides 80, 81. However, new techniques such as lamination in which several layers of wood are bonded by glue has increased structural usage.

Slide 82. Plywood is a material used extensively and formed by laminating with glue several layers of wood with the grain at right angles to each other.

Slides 83, 84, 85, 86. Masonry includes brick, stone, and concrete blocks. Masonry requires joining of each unit by means of a bond, such as mortar.

Slides 87, 88. Stone masonry is expensive and usually reserved for monumental buildings. Stone buildings can stand almost forever. The use of stone means great mass and resistance to compression but not to tension.

Slides 89, 90. Brick is a mixture of the four elements: earth, air, fire, and water.

Slides 91, 92, 93. Brick has a more intimate scale than stone, and varying textures and colors are available in brick.

Slide 94. Brick is also strong in resisting compression but not tension, and another structural drawback is that hand labor is required for bricklaying.

Slides 95, 96, 97. Steel is considered the strongest and most reliable structural material. Steel lends itself to a skeleton-type framework.

Slide 98. Connections are important in steel structures because complex stress patterns may develop around riveted areas. Welding permits a more continuous flow of forces and reduces shear stress.

Slide 99. Steel is light, strong, and ductile. Because of its great strength, steel members can be made quite slender and steel cables have made possible a new kind of light and elegant structure.

Slide 100. Steel may tend to melt in fire situations, and it oxidizes on contact with air, but these drawbacks are being researched for new solutions.

Slides 101, 102, 103, 104. Aluminum is used widely in building, usually nonstructurally, such as for siding or door and window frames. In some cases, such as geodesic domes, it is used structurally. Its chief structural advantages are its light weight and resistance to corrosion; however, it has low stiffness and may buckle.

Slides 105, 106. Reinforced concrete is one of the most widely used materials.

Slide 107. Concrete resists compression well, but if it is to be used in beams and girders it must also be made to resist tension.

Slide 108. Normal reinforced concrete is made by adding steel mesh, bars, or rods to unhardened concrete. It is stronger than ordinary concrete, but the steel is not stressed, and acts with the concrete when it is loaded, and cracking may occur.

Slide 109. Prestressed concrete is another form of reinforced concrete. Highly tensioned steel wires or tendons are stretched through the concrete and fastened, "locking in" stresses.

Slide 110. Prestressing is done by pre-tensioning in which steel wires are stretched through an empty form, stressed by hydraulic jacks, and concrete is then poured over the wires. When the jacks are released, the steel tries to shorten and the stress is transferred to the concrete.

Slide 111. Post-tensioned concrete is made by pouring concrete into a form and allowing it to harden. Channels are made for the wires, which are slid through and then stressed by the hydraulic jack. The stresses are again transferred to the concrete. Both of these methods have a tendency to arch the beam upward. When a load is put on the beam it settles downward, and the concrete does not have to resist tension at any time, because of the locked-in stresses.

Slides 112, 113, 114. These concepts of reinforcing have helped concrete to be used in longer spans. Concrete, like bricks, may be made with a variety of interesting textures and colors.

Slide 115. Plastics could be considered the material of this age.

Slide 116, 117. In architecture, plastics have had a wide non-structural use from roof, floor, and wall coverings to pipes and insulation, to windows and skylights. Plastics are synthetic organic materials based on carbon compounds and capable of being reformed by heat or pressure.

Slide 118, 119. For structural use, plastics which lack stiffness are combined with high strength glass fibers to produce fiberglass reinforced plastic.

Slide 120. Plastic may also be laminated or sprayed on membranes to provide a protective covering.

IV. Structural Systems

Slides 121, 122. In analyzing structural systems, there are several items to consider:

(1) How specific members function. For example, columns support in compression, and beams span.

Slide 123. (2) The geometry of the form and the way the load is carried. An arch and a beam span horizontally but have different forms; an arch and a cable span horizontally, but carry loads very differently.

Slide 124. (3) The way the members are joined since connections help transmit forces.

Slides 125, 126. The bearing wall distributes vertical compressive forces downward to the ground. Compressive materials like stone or brick are mostly used.

Slide 127. Loads on bearing walls should be uniformly distributed, and openings should be framed so as not to disturb the continuity of the wall.

Slide 128. Concentrated, widely-spaced loads are transmitted to the wall, and may crush it unless reinforcing, such as pilasters are used, but then the bearing wall begins functioning like a post-and-beam system.

Slide 129. Stability in a bearing wall may be obtained by adding mass,

Slides 130, 131. or through changing its geometry. This chapel at Massachusetts Institute of Technology was designed by Eero Saarinen.

Slide 132. The bearing wall is a major structural element in this design for an administration building by I. M. Pei. The bearing wall occurs at both ends of the building and is given stability by making it angular in shape. The sides help support each other.

Slide 133. The main characteristics of a bearing wall are: (1) It resists compressive forces and utilizes compressive materials; (2) it does not span space, but supports; (3) uniform loading produces the greatest structural efficiency; and (4) stability can be increased by positioning the form as well as adding mass.

Slides 134, 135. The post-and-beam system transmits loads horizontally by beams and vertically by posts. The beam spans and the post supports. The beam must resist bending and shear forces, while the post must resist compressive forces.

Slide 136. A post-and-beam system can be used as a multistory frame, building one system on top of another.

Slide 137. The column below each system must support its own load plus that above; therefore, the lower columns will be larger than the upper ones. This system carries vertical loads better than horizontal ones.

Slide 138. This parking garage in New Haven illustrates the fact that post-and-beam construction can be simply stated without appearing static or dull. Paul Rudolph has designed a steel girder-in-concrete system that is visually exciting and makes a strong statement of its supporting and spanning functions.

Slides 139, 140, 141. Rudolph has also gone beyond the box in his design for the Art and Architecture Building at Yale University, which uses the post-and-beam system in a dramatic manner. The post-and-beam construction carries the eye up and around the building. The vertical reinforced concrete piers carry the floors somewhat like trays between them. The visitor has the visual surprise of passing between two towering concrete monoliths to an open space.

Slide 142. I. M. Pei and Associates have extended the multistory steel skeleton to an elegant slender needle of a building.

Slides 143, 144. The John Hancock Building in Boston will be nearly sixty stories high and the exterior will be covered with reflective glass, which should make the building seem even lighter and more delicate. The unusual shape of the frame is an interesting variation of the traditional steel and glass high-rise box.

Slide 145. A beam in a post-and-beam system can be utilized structurally in different ways. A simply supported beam is supported on each end, but the beam can rotate or expand and contract. The beam is also subject to bending.

Slide 146. It can be made more efficient by separating the compression and tension stresses as much as possible and making the beam deeper. To minimize weight and twisting, triangular openings can be made in the neutral section of the beam where tension and compression do not occur. The beam begins to act like another system, the truss.

Slide 147. If beam supports are shifted toward the middle, the beam is cantilevered.

Slide 148. The Newark Airport control tower is an example of structure that uses the single cantilever.

Slide 149. Three reinforced concrete beams carry the loads to the massive supportive column which transfers them to the ground. This column must be quite large in order to support the weight of the building which cantilevers over it, and to keep it from looking unstable.

Slide 150, 151. Loading a cantilever between supports may cause the ends to rise, while uniformly loading the cantilevered beam causes the cantilevered ends to balance each other and counter the stresses of the central span. This makes an increased span possible, without increasing the stresses. The beam area of a cantilevered beam can be reduced by about one-third of the area of a simply supported beam.

Slides 152, 153. Using the cantilever adds both structural and visual lightness, and provides a more interesting and less box-like building.

Slides 154, 155, 156. The Solomon R. Guggenheim Museum, designed by Frank Lloyd Wright, uses giant, spiraling reinforced concrete cantilevers that carry the eye upward. The sheer massiveness of the spirals is balanced by the rectangular forms at the base, which also add a feeling of stability and support. Inside, interestingly enough, the spiral is reversed and spreads out at the base.

Slides 157, 158. This building at Massachusetts Institute of Technology uses a cantilevered treatment on a rectangular form to appear lighter and less box-like.

Slide 159. The Whitney Museum in New York City, designed by Marcel Brewer, cantilevers on one side to form a sculptural facade; it has the feeling of an inverted step-pyramid. The overhang is the largest at the top, as in the Guggenheim Museum.

Slide 160. Beam ends can be fixed into a support and the beam becomes more rigid and will not rotate. This means the beam can carry as much as fifty percent more loading and is stiffer.

Slide 161. Also, the beam may be attached rigidly to the supports, and the joints can then transfer bending among all the members. This is called a rigid frame, and all the members share the loading. Steel and reinforced concrete are well suited for rigid-frame construction.

Slides 162, 163. Kevin Roche, John Kinkeloo and Associates developed a striking variation on this type of post-and-beam system.

Slide 164. They designed four towers and a central core, which are the structural supports for the building. Steel girders span from the towers diagonally to the core, and transversely to the supports.

Slide 165. A continuous beam extends over more than two supports and may be used in long spans because deflection is reduced.

Slide 166. The major characteristics of the post-and-beam system are: (1) It transfers forces horizontally and vertically; (2) beams must resist bending; (3) beams may be used in a variety of ways; and (4) steel, wood, and concrete are used for the post-and-beam system.

Slides 167, 168. The truss is a framework of short straight members in a triangular form. The members resist direct tension and compression, but no bending forces occur.

Slide 169. The triangle is an inherently stable form and is the only form that can hold its shape if all the joints are hinged.

Slide 170. The tension members of a truss are more efficient and lighter than the compressive ones, so they should be used whenever possible. The truss is structurally efficient by using minimum mass and maximum separation.

Slide 171. The Vierendeel truss combines the rigid frame form with the truss principle. The diagonal member is eliminated and space is freed.

Slides 172, 173. The Yale University Rare Book Library illustrates the use of the Vierendeel truss as the principal structure for the four sides of the building. The steel structure is completely welded, which permits a more continuous flow of forces than rivets, and the trusses support marble and onyx panels. The building is supported at only four points; this type of truss is particularly good for resisting strong wind loads.

Slide 174. Steel and reinforced concrete are used in truss systems. The truss is particularly well suited to long spans because of its light weight and stability. The truss is characterized by:

Slide 175. Short rigid members in a triangular form; direct tension and compression which occur and eliminate bending; inherent stability in the triangle form; a variety of truss shapes; and the ability to be used in long spans.

Slide 176, 177. The space frame is made up of intersecting trusses. The use of the triangle in two or three dimensions insures stability,

Slide 178. and simple compression and tension are developed.

Slide 179. Large concentrations of forces are developed at the points of supports, and a lattice support which is a trussed form creates a more gradual distribution of the forces from the frame to the support.

Slide 180. The space frame can be used in other shapes than a flat span. This roof, designed by Pier Luigi Nervi, is called a lamella roof and is designed on a skewed grid. The short, stiff beams are at angles to the base and can increase the loading capacity up to fifty percent.

Slide 181. The geodesic dome is a space frame with a double curved surface. This dome, designed by R. Buckminster Fuller for Expo '67, is very light and rigid. Exterior triangulation forms a three-quarter sphere and the interior skin is made up of acrylic plaster units. The frame is constructed of light-weight steel. The connecting units are very important in resisting and transmitting forces in the dome frame, and the cost of connections weighs heavily in overall building costs.

Slide 182. The geodesic dome can be designed with a different combination of triangles, it is light-weight and stable, and it is easily prefabricated and assembled.

Slide 183. This dome, which has a fabric skin, was assembled in a few hours for the International Design Conference at Aspen, Colorado. Difficulties with this system include providing well-integrated openings and interior spaces and various service systems, such as lighting. The complexity of stresses that occur at the dome makes exact calculation of stress very unfeasible, and the dome is said to be statically indeterminate.

Slide 184. In summary, the space frame: (1) Uses the truss in two or three dimensions; (2) develops direct tension and compression; (3) needs well designed connections to transmit and resist internal stresses; and (4) may be used for long, flat spans or curved spans as a lamella roof or geodesic dome.

Slides 185, 186. The slab is a one-piece or monolithic form that distributes loads in more than one direction. The slab must resist forces of bending, shearing, and twisting. Reinforced concrete, which may be cast all in one piece, has made this monolithic form possible.

Slide 187. The slab may be supported in various ways: a one-way slab is supported on two edges and reinforced in one direction; it may be quite susceptible to bending. A slab supported on all four edges and reinforced in two directions transmits forces in two directions, developing complex stress patterns. A two-way slab distributes forces like a network of intersecting, side-by-side beams and girders, which makes calculation of the precise forces and stresses very difficult, so this structure is called statically indeterminate.

Slides 188, 189. Instead of edge supports, the slab may use columns or posts. Stresses are quite concentrated at points of support and often heavy capitals or shear connections must be used with the column to prevent "punching" shear where the slab and column connect. The Carpenter Art Center, designed by Le Corbusier, uses the column-and-slab system of building.

Slides 190, 191. The engineers who worked on the Carpenter Art Center had a difficult time because Le Corbusier demanded proportionately slender columns for the load they had to carry.

Slide 193. Reinforced concrete floor slabs are used here with tempered plate glass slabs for walls. The building expresses a structural unity and clarity, and the structure and interior spaces reiterate a total design environment.

Slide 194. The Eastern Airlines Terminal, designed by Yamasaki, also uses the slab-and-column system.

Slide 195. The slab is extended beyond the building and the ribbing above the columns relieves some of the stress in the slab. The structural efficiency of the slab can be improved by ribbing as seen in the

Eastern Airlines Terminal. If the ribs intersect and form a grid, a "waffle" type slab results.

Slides 196, 197, 198, 199, 200. Paul Rudolph combines this type slab with massive supporting columns in the Employment Security Building in Boston's Government Center. The building is exciting to look at and move through, and seems to invite one to keep turning the next corner to see what is there. The structure uses massive concrete piers and cantilevers and the concrete texture provides an interesting surface variation. Because the facade is varied, the size of the building does not seem overwhelming but develops a scale that one can relate to. Rudolph is able to use traditional building techniques to create very sculptural buildings.

Slide 201. The folded plate is another variation of the slab system that reduces the bending tendency. The folded plate acts like a series of small slabs tilted against each other and joined. A folded plate resists forces by acting like a beam and a slab.

Slides 202, 203. Forces are carried perpendicular to the fold as if in a one-way slab, and the forces are then transferred longitudinally as if by beams, to the supports. The plates act like a tilted beam with the upper part in compression and the lower in tension. The strength of a folded plate depends on its thickness and how steeply it is pitched. As the pitch decreases, the plate is less efficient.

Slide 204. To prevent the folded plate from collapsing, a restraint at the ends of the plate or at points of support must be added. Tie rods and bearing walls or other transverse stiffeners are often used to prevent the thrust from causing collapse. The folded plate provides a varied roof treatment, and is structurally more efficient than a flat slab.

Slide 205. In summary, the slab system is: (1) Monolithic in form and resists bending and shear stresses in one or more directions; (2) supported on two or four edges or by columns and posts; and (3) made more efficient by adding ribs or folding it to resist stresses.

Slide 206. The arch is a spanning system that reduces compressive forces and is a structural form that is the basis of two other systems, the vault and the dome.

Slides 207, 208. The ideal arch form is a catenary which occurs if a cable is held between two points. The forces will try to follow the easiest path, and the chain will assume a natural pulling shape. Another way to understand a catenary curve is to imagine it as a cable with equal loads attached at equal intervals to its entire length. If the catenary curve is inverted, an arch is formed and an arch curve and the line of stress are the same line. The arch can span space more efficiently than a post-and-beam because the beam develops compressive and tensile stresses, and has vertical reactions only as the forces move down the supports. An arch has all internal compressive forces, and uses a horizontal thrust and a vertical reaction in channeling the forces to supports.

Slide 209. This exhibition hall designed by Nervi uses a series of wide parallel arches for a large, unobstructed span. The parabolic arches are of reinforced concrete; forked buttresses support three arches each, collect their loads, and transfer them to the ground. Thrust is resisted by ties which are underground.

Slide 210. The thrust may be resisted by tie rods or by buttressing or by using the arch as part of a series. In this way, each arch works together in resisting thrust, which is the force that would make the arch spread.

Slide 211. An arch may be rigidly connected to supports, or it may have one or two hinges which let the arch move, in case of temperature fluctuations or settlement at the supports. This reduces bending stresses in the arch.

Slide 212. In summary, the arch is: (1) A curved form that spans and develops compressive forces; (2) a curve that should be built as close to its catenary as possible to carry loads efficiently; and (3) a graceful form which may be used for large unobstructed spans.

Slides 213, 214. The vault takes the form of an arch extended along a plane, and it can distribute its loads either by arch action alone to supports or by a combination of arch and slab action.

Slide 215. The short barrel vault, or short cylinder shell never really develops longitudinal action. The space between supports acts like a slab in transferring loads horizontally to the arched supports, which transmit it to the ground.

Slides 216, 217. The curve of the arch coincides with the span. If a series of short shells are used together, stiffening ribs of laminated wood may be used for stability. The short shell arch keeps the parabolic curve of the arch form.

Slides 218, 219. The long barrel vault curves at right angles to its span, and develops longitudinal action. It may be considered as a series of longitudinal adjoining beams, arranged in a curved form. The forces are transferred as if by beam action longitudinally to the curved supports. The longitudinal elements restrain each other from deforming and the carrying capacity is strengthened. Transverse stiffeners or buttressing may preserve the shape of the long barrel vault and keep it from spreading.

Slides 220, 221, 222, 223. The St. Louis Airport Terminal Building, designed by Yamasaki, uses three intersecting vaults. Stiffeners at the roof edges and along the lines of vault intersection transfer forces to the four points of support. The thrust of the vault is resisted by ties beneath the floor. Yamasaki repeats the theme of intersecting vaults in the interior of the Boston Eastern Airlines Terminal. The widely spaced vaults repeat the lines of ribbing that occur on the overhanging roof outside.

Slide 224. Materials used for vaults vary; often masonry or corrugated steel has been used. Contemporary vaults make use of reinforced concrete to make the roof lighter.

Slide 225. The main characteristics of the vault are: (1) Forces are transmitted through a combination of arch, or arch and slab action; and (2) short barrel vaults do not develop longitudinal transmission of forces like long barrel vaults do.

Slides 226, 227. The dome is a structural system based on the rotation of an arch around a central axis. A cylinder takes the arch form in one direction while the dome is a doubly-curved surface.

Slide 228. The dome can be a light, strong, resistant structure which encloses a maximum of space with a minimum of material, and has been developed naturally in forms like a sea urchin.

Slide 229. The forces which act on a dome flow in the direction of the meridians and parallels which divide the dome. There is a transitional line in the dome which determines the action of forces. Above this line, the dome develops compressive stresses, while below it, it develops tensile stresses. Compressive forces follow the direction of the meridians while tensile forces move along the parallels.

Slide 230. The traditional dome is often made of masonry or brick. The compressive forces develop in the upper part of the dome, and tensile forces in the tower. Tie rods or buttressing keep the dome from spreading at the base because of horizontal thrust.

Slide 231. Contemporary thin-shell structures have begun to replace the traditional masonry domes. This dome, designed by Nervi, will house the Norfolk, Virginia Convention Hall. The dome is a thin shell of reinforced concrete which transmits forces to the large concrete V-shaped supports. Reinforced concrete domes can be as thin as two inches, and are rigid and resist bending. The edge stiffener around the dome aids in distributing forces without disturbing the continuity of the thin shell.

Slide 232. The Astrodome in Houston, Texas utilizes a steel framework for the dome structure, and the framework is covered by a thin acrylic plastic and steel shell, which lets much light into the dome.

Slide 233. In summary, a dome is: (1) An arch revolved around a central axis; (2) capable of large spans with little material; (3) a form which develops compressive and tensile forces along the meridians and parallels; and (4) usually made of reinforced concrete which allows a thin shell.

Slides 234, 235. The shell is a structural form whose surface is singly or doubly curved. Forces are transmitted along or tangential to the curved surface to supports. Two characteristics of the shell are its curvature and its rigidity. The curve of the shell has a tendency to cause direct stresses of tension, compression, and shear, which are transmitted along the curve to supports. The thinness of the shell works with the curvature to resist bending.

<u>Slide 236</u>. Forces develop along the surface of a shell, or tangentially, rather than within it, as would happen if the shell had substantial depth. Therefore, a shell should be made as thin as possible.

<u>Slide 237</u>. Loads should be uniformly distributed and not concentrated. A concentrated force or load acting on a shell may cause failure. The shell can take a variety of forms. The thin cylindrical shell or barrel vault, and the shell of rotation, or contemporary dome have already been discussed.

<u>Slide 238</u>. The hyperboloid is another commonly designed shell. The stresses were not calculable for this shell, so wooden ribs were added.

<u>Slide 239</u>. Another commonly designed shell form is the hyperbolic parabola. This saddle-shaped form occurs when horizontal and vertical parabolas intersect and are hung between two upright parabolas. The hyperbolic paraboloid is a popular shell design because it creates an interesting warped surface.

<u>Slides 240, 241</u>. The M.I.T. Auditorium designed by Saarinen, is a shell that uses a section of a hemisphere. The shell segment is triangular in shape, and the dome rests on three buttressed supports, which are connected by ties to resist thrust. The shell is about three and one-half inches thick, and the edges of the dome have been reinforced by thick arched beams which are supported by closely spaced columns.

<u>Slides 242, 243, 244</u>. A shell structure that became world famous from its conception is the sail shell designed for the Sydney, Australia Opera House. The sails are made of reinforced concrete which is a natural material for shell structure, since it can be made thin and strong; and the sails seem to billow out as if they were catching the breeze from the

bay. Shell design is hampered by complex mathematics, keeping the shell uniformly thin and avoiding concentrated loads.

Slide 245. In summary, the shell is: (1) A singly or doubly curved surface; (2) characterized by rigidity and curvature; (3) designed as thin as possible to transmit forces tangentially and to avoid bending; and (4) made of a light, strong, formable material such as reinforced concrete.

Slides 246, 247. Tension structures have become increasingly important. If the pure compressive arch form is inverted, the result is a pure tension form. The principal characteristic of tension is pulling or stretching and the tension member follows the line of its stresses. In a tensile structure, loads are distributed through cables or membranes to supports, and the system is designed to transmit tension forces. The cable is a major element in tensile structures. It may be considered a flexible member because it has a small lateral dimension in relation to its length.

Slide 248. The shape of a cable is governed by the load it bears and the ideal tensile shape is called a parabola. It occurs when equal loads are horizontally and equally spaced along a cable. The parabola is to tension as the catenary is to the arch.

Slide 249. A cable which is draped between two supports develops a horizontal thrust, in the same manner as the arch. The less slope there is in the cable, the greater the horizontal thrust and the larger will be the supports.

Slide 250. The cable changes shape under loading because it always tries to assume the ideal curve for each load. This flexibility is a structural handicap, because stability is a necessary requirement of structure. There are means of stabilizing the cable, as well as reducing its susceptibility to wind uplift and flutter. Dead loads may be applied to the structure to increase the weight, in the form of ties which stress the cable and hold it in place. Or the cable may be stiffened and made into an inverted arch. Or the cable may be stabilized by adding transverse cables.

Slide 251. Cables may be draped across single perpendicular spines as in suspension bridges.

Slide 252, 253. The Boston Institute of Contemporary Art is housed in a steel modular unit which hangs from large steel frames, in a similar manner.

Slide 254. Or cables may be draped across inclined supports, as in the Dorton Arena in Raleigh, North Carolina. This building is quite famous for being one of the earliest tensile structures of such large scale ever built in the United States. It is a dynamic expression of a tension system which covers a large space. The mutually opposed steel cables, the longest of which is 300 feet, are stretched between two inclined, interlocking arches. The arches seem to be pulling back against each other, and pulling the cables taut in the process.

Slide 255. The roof is a doubly curved hyperbolic surface, and is somewhat stable against flutter created by wind forces.

Slide 256. Closely spaced columns around the perimeter support some of the weight of the reinforced concrete arches, and carry the glass facade.

Slide 257. Cables may also be used in a system with tension and compression rings, in a structure similar to a bicycle wheel; the spokes are cables tensioned between an inner tension ring and an outer compressive rim, where the thrust is resolved and vertical loads are transferred to the ground.

Slide 258. The U. S. Pavilion at the World's Fair held in New York is designed on this principle. The cables are stretched from an inner ring out to the large concrete columns, where the tensile forces are transmitted and carried to the ground. This is a very stable system, with minimum flutter.

Slide 259. The Ingalls Hockey Rink at Yale, designed by Saarinen, integrates structure and function to create an unusual tensile building.

Slide 260. Steel cables are suspended between two horizontal arches on their sides and a central reinforced concrete parabolic arch which spans almost 250 feet. Cross cables stabilize these suspended cables. The roof is of lightweight wood, which adds stability without increasing the weight greatly.

Slide 261. Tents are another form of tension structure. The tent fabric is an extension of the cable, and no other form seems to flow so spontaneously from its structural principle. The form of the tent is itself the structure and the forces that act on the tent are resolved and distributed through the tent surface to the supports.

Slide 262. Tents are made of stressed fabric, and to increase stability and fluttering, the tent may be secured by ties and guy wires. Supportive masts or arches or ribs are essential to the tent to give it shape.

Slides 263, 264. This tent which covered the German exhibition at Expo '70 was designed by Frei Otto. The plastic coated membrane is tightly stretched over steel supports and anchored to the ground.

Slide 265. A fabric or membrane may be structurally sounder if it is tensioned before it is loaded. An umbrella is an example of a "tent" with locked-in stresses; the steel ribs tension the cloth and give it shape when the umbrella is opened.

Slide 266. In summary, a tension structure: (1) Distributes loads by tension through cables and membranes; (2) may require external anchoring or opposing cables to prevent a cable changing shape; and (3) may be draped in different ways between supports.

Slide 267. A pneumatic structure is made up of a membrane which transmits tensile forces and is stretched and supported by pressurized air.

Slide 268. The air is actually the main load-bearing element and the stretched membrane serves to transfer forces caused by differing internal and external air pressure to the ground.

Slide 269. Air pressure inside is maintained mechanically, and airlocks are the means of entrance into the structure.

Slide 270. A pneumatic structure may have a single skin, and the system would fail if the skin were punctured. The loss in pressure would be so slow, however, that occupants would not be endangered. A double membrane air structure has two layers of fabric with pressurized air between them as well as in the building's interior. Failure of one part doesn't necessarily mean collapse of the entire structure. Even if both members fail, escaping air loss is still quite gradual.

Slide 271. Although pneumatic structures so far have been spherical or combine the sphere and half-cylinder, any variety of shapes and arrangements is possible. The shape can also be varied by the use of ropes and cables across the membrane. This provides variety and reduces membrane stress by collecting forces and transferring them to supports through the cables. The U. S. Pavilion at Expo '70 in Japan uses a very low pneumatic structure, spanning the distance of two football fields. The pneumatic structure is easily portable and uses a minimum anount of material for long spans. Multistory air-supported structures are being designed, which will make the system more widely used.

Slide 272. In summary, a pneumatic structure: (1) Uses a membrane stretched by pressurized air to transmit forces to supports; (2) may have a single or double membrane; and (3) is light, portable, and uses minimum material for maximum spans.

CHAPTER V

SUMMARY AND RECOMMENDATIONS

Summary

This project was undertaken to gather a wide range of information on architectural structure and materials from sources often unavailable to those who are not studying to become architects and engineers, and to present it in a simplified form. The written material was developed from the premises that the quality of man's visual surroundings is as much endangered today as his natural surroundings, and that a development of visual integrity despends largely on an understanding of the interrelatedness of form, structure, and influence of space by those who design the visual environment. To gain this control, the designer or designers must gain a general sense of structure which Kepes calls the ". . . power to see our world as an interconnected whole" (15:ii). While the architect and engineer are trained in understanding structure and form, they often lack the humanistic and behavorial understanding of the way their spaces influence people. At the same time, the interior designer may have received much training in the social aspects of design, space, and appreciation of form, yet have little understanding of how a structure actually exists. The interior designer and architect lack a common vocabulary, and to function as a design team, they should have some understanding of common design principles and understand why some solutions to a design problem are feasible and others are not.

Terms which were to be used in the paper were defined and the meaning of structure was investigated. Most authors cited structure as the essential beginning of the design process, but not its dictator. Structure was seen as a means of enclosing space, providing shelter and space for man's activities, and as a visual expression of man's sense of beauty. While structure does not have to be visible, there should be an integrity of structure and the form it conveys. Choice of materials and structural systems may result in a very real feeling of rightness or wrongness about the building as a whole. The use of visual illustrative material was developed in this project to make it one which could be used. It was designed specifically to acquaint beginning interior design students or a general audience with the principles of architectural structure and materials.

The principles of structural action are important in understanding how a structure functions, and they can be understood without mathematics or physics. People have intuitive recognition of certain structural principles from everyday experiences, so from this point it is an easy step to understanding why and how a structure works.

A building must resist forces acting on it externally and internally if it is to maintain a state of equilibrium and remain standing. The forces applied must meet with equal resisting forces for structural equilibrium to occur. Structural efficiency is achieved through the simplest routing of forces to the ground. Forces which the structure must resist may consist of live and dead loads, as well as static and dynamic loads. Forces may also be distributed uniformly over the structure or concentrated in a small area. Internal forces or stresses may occur, as well as external forces, and these stresses are accompanied by an often visable deformation called strain. A structure may have to resist the forces of compression, tension, shear, torsion, and bending, or any combination of these forces.

Certain forces may require specific materials, and each material has a unique design capacity. The major materials in use today include: wood, which is organic and used mainly for small scale building; masonry, which implies permanence and great mass and may be subdivided into stone, brick, and concrete blocks; steel, which has high strength and utility and has made tensile structures possible; aluminum, which is lightweight and often used in geodesic dome structures and even some rigid frames; reinforced concrete, which can also be prestressed to provide greater utility; and plastics, which are often combined with glass fibers, and are being used on a wider scale.

Major structural systems may depend on the choice of materials and forces that must be resisted.

The bearing wall is a structural system which resists compression, supports weight, and is usually made of masonry. The post-and-beam system transfers loads horizontally and vertically, in tension and compression. Beams may be simply supported, cantilevered, fixed into two supports or continuous over several supports. The truss is a structural system that uses short straight members in a triangular form. Only direct tension and compression occur, and the system can be used for long spans. The space frame is a three dimensional truss system. The slab which is monolithic in form, distributes loads in one or two directions and must resist bending and shearing. The arch is a curved form that resists compression and is the basis for two other systems, the vault and the dome. The vault system may develop both slab and beam action and must resist horizontal thrust, like the arch. The dome resists compressive and tensile forces in the direction of its meridians and parallels and can enclose great space with minimum material. The shell system is characterized by its thinness, its rigidity, and its curvature and often is made of reinforced concrete which can be made in a thin and curved form. A tensile structure distributes its loads through steel cables or membranes and must be stabilized in some manner. Pneumatic structures are supported by an internal air pressure which is greater than the external air pressure. The membrane of the system transmits tensile forces to the ground.

The future design of structural systems may include a much greater use of prefabricated systems and on-site construction. Also, architecture may be regarded as more closely united with cultural change and less permanent in nature than it has been. Sophisticated mechanical systems may erect structures and disassemble them, as well as regulate any internal movement by sensors. Computers may be utilized more fully as a pardner in the design process, and people in all phases of design may work together as a team in developing total environmental design.

Recommended Uses

This project was designed to present these ideas in an open-ended package. It should serve as the launching point toward a more creative method of educating our sense of vision. The slides, film, and written material can be used in a number of ways. The description of the slides may be read while the slides are shown, as a simple classroom supplement in an interior design or similar type course. An alternative method would be to record the written information on tape cassettes and synchronize it with the slides. This type of arrangement could also be used as a display, an exhibit, or to provide mini lessons outside the classroom situation. The written material in the review of literature could be used as background information or to provide even more depth in the study of structures, preceding the slides, or it could be set up as part of a multimedia exhibit, in which the film and slides are shown simultaneously, while the description of slides is played on a tape recorder. In a classroom presentation, an introduction should precede the film clip. When the slides are shown, it is suggested that the presentation be stopped for intermission (or divided into two or three parts), after the sections concerning structural principles and the use of materials.

Recommendations for Future Study

The use of a visual presentation can be a fairly low-cost means of presenting information. The time spent in preparing such a presentation can be enormous, but the value of visual materials makes this type of effort well worthwhile. The person who develops a multimedia presentation has the chance to become creatively involved in the teaching and design process. To carry this idea even further, individual students may develop their own visual projects, either as an outgrowth of one presented to them, or in place of it entirely. Schools and universities should come to recognize the need for using cameras, video tape, recorders (all media instruments) as valuable tools in the design process, and students should have access to their use. Film and camera equipment does not need to be sophisticated; in fact, it should be simple enough to not get in the way of the creative process and make the project difficult. Whole libraries of slides and simple films could be developed on all areas of design and the environment, and they could be created as term projects or theses. In this way, the design student may begin to have an increased awareness of design criteria and design alternatives that are available.

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APPENDIX A

SOURCE OF REPRODUCED SLIDES

Slides 28, 231. The Norfolk Convention and Visitors Bureau.

Slides 149, 181, 232, 258. Mr. Albert G. H. Dietz, Plastics for Architects and Builders. Cambridge, Massachusetts: The MIT Press, 1969.

Slides 180, 209, 259, 260, 261, 263, 264, 266. Mr. John MacRae.

Slides 242, 243, 244. Mr. Gordon Nelson.

APPENDIX B

IDENTIFICATION OF STRUCTURES

<u>Title Slide</u>

1. Automobile exhaust.
2. Water.
3. Eroded land.
4. Highway.
5. San Francisco, California.
6. Billboards.
7. Motel Building, Raleigh, North Carolina.
8. Boston, Massachusetts.
9. Musicians, Union Grove, North Carolina.
10. Construction, Raleigh, North Carolina.
11. Construction, Raleigh, North Carolina.
12. Frozen earth.
13. Office building, New York City.
14. Construction, Boston, Massachusetts.
15. Architect's office, Raleigh, North Carolina.

16, 17. Employment Security Division Office Building, Boston, Massachusetts. Architect: Paul Rudolph.

18. Lever House, New York City. Architects: Skidmore, Owens, and Merrill.
19. Aerial view of Raleigh, North Carolina.
20. Illustration of design and the environment.
21. Apartment buildings, Raleigh, North Carolina.

22. Close-up view of sea shells.

23. Two people, Henderson, North Carolina.

24, Employment Security Division Office Building,
25, Boston, Massachusetts.
26. Architect: Paul Rudolph.

27. C.B.S. Office Building, New York City. Architect: Saarinen.

28. Model of theater, Norfolk Convention Center, Norfolk, Virginia. Designer: Pier Luigi Nervi.

29. Community Services Building, New Haven, Connecticut.

30. North Carolina National Bank Building, Raleigh, North Carolina.

31. Drive-in restaurant, Raleigh, North Carolina.

32. C.B.S. Office Building, New York City. Architect: Saarinen.

33, Office building, Raleigh, North Carolina.
34,
35 & 36.

37. Mobile office unit, Raleigh, North Carolina.

38. Title slide.

39. Ladders.

40. Employment Security Division Office Building, Boston, Massachusetts. Architect: Paul Rudolph.

41. Illustration of equilibrium.

42. Illustration of transfer of forces.

43. Illustration of failure.

44. Illustration of flow of forces.

45. Columns of a church, Raleigh, North Carolina.

46. Illustration of transfer of forces.

47. Illustration of live loads.

48. Burlington Industries Corporate Headquarters, Greensboro, North Carolina.

75. Office building, Raleigh, North Carolina.

76. Trees.

77. Wooden drawer.

78. Southern yellow pine trees.

79. Illustration of failure in wood.

80, 81. Construction, Chapel Hill, North Carolina.

82. Illustration of wood lamination.

83. Title slide.

84. Bricks.

85. Stone wall, Raleigh, North Carolina.

86. Concrete blocks.

87. School building, Harvard University, Cambridge, Massachusetts.

88. Old residential building, Boston, Massachusetts.

89. Brickwork detail, Boston, Massachusetts.

90. Brick residence, Boston, Massachusetts.

91. North Carolina National Bank Building, Raleigh, North Carolina.

92. Bricks.

93. Brick wall.

94. Environmental Protection Agency, Raleigh, North Carolina.

95. Title slide.

96. Construction, Cambridge, Massachusetts.

97. Construction, Raleigh, North Carolina.

98. Construction, Cambridge, Massachusetts.

99. Delaware Memorial Bridge.

100. Steel oxidizing.

101. Title slide.

102. Aluminum door frame.

103. Aluminum siding.

104. Aluminum geodesic dome.

105. Title slide.

106. Community Services Building, New Haven, Connecticut.

107. Concrete beams.

108. Illustration of reinforced concrete.

109, 110, 111. Illustrations of prestressed concrete.

112, 113, 114. Concrete textures and colors.

115. Title slide.

116, 117. Plastic roofs, Raleigh, North Carolina.

118. Office building, Cambridge, Massachusetts.

119. Detail of fiberglass used in construction.

120. Plastic coated membrane.

121. Title slide.

122. Construction, Raleigh, North Carolina.

123. Illustration of arch, beam, and cable.

124. Illustration of connections.

125. Title slide.

126. Dormitories, Yale University, New Haven, Connecticut. Architect: Saarinen.

127. Office building, Cambridge, Massachusetts.

128. Office building, Raleigh, North Carolina.

129. Office building, Boston, Massachusetts.

130, Chapel, Massachusetts Institute of Technology, Cambridge,
131. Massachusetts. Architect: Saarinen.

132. Office building, Boston, Massachusetts. Architect: I. M. Pei.

133. Chapel, Massachusetts Institute of Technology, Cambridge, Massachusetts. Architect: Saarinen.

134. Title slide.

135. Illustration of post-and-beam.

136. Construction, Raleigh, North Carolina.

137. Illustration of multistory building.

138. Parking garage, New Haven, Connecticut. Architect: Paul Rudolph.

139, Art and Architecture Building, Yale University, New Haven,
140, Connecticut. Architect: Paul Rudolph.
141.

142, John Hancock Building, Boston, Massachusetts.
143, Architect: I. M. Pei.
144.

145. Illustration of simply supported beam.

146. Illustration of triangulation in a beam.

147. Illustration of cantilevered beam.

148, Newark Control Tower, Newark, New Jersey.
149.

150, Illustration of loading in a cantilevered beam.
151.

152. Detail of a cantilever.

153. Detail of cantilevers.

154, Solomon R. Guggenheim Museum, New York City.
155, Architect: Frank Lloyd Wright.
156.

157, Student Union Building, Massachusetts Institute of Technology,
158. Cambridge, Massachusetts.

159. Whitney Museum, New York City. Architect: Marcel Brewer.

160. Illustration of a fixed beam.

161. Illustration of a rigid frame.

162, 163, 164. Knights of Columbus Building, New Haven, Connecticut. Architects: Kevin Roche, John Dinkeloo and Associates.

165. Illustration of a continuous beam.

166. Post-and-beam construction.

167. Title slide.

168. Truss.

169. Illustration of stability of a triangle.

170. Tension and compression members of a truss.

171. Illustration of Vierendeel truss.

172, 173. Rare Book Library, Yale University, New Haven, Connecticut. Architects: Skidmore, Owens, and Merrill.

174. Truss.

175. Truss.

176. Title slide.

177. Space frame.

178. Illustration of a space frame.

179. Illustration of a lattice support.

180. Sports Palace, Rome. Designer: Pier Luigi Nervi.

181. U. S. Exhibition, Expo '67, Montreal. Designer: R. Buckminster Fuller.

182. Dome assembly, Aspen, Colorado.

183, 184. Geodesic Dome, Aspen, Colorado.

185. Title slide.

186. Design Research Building, Cambridge, Massachusetts. Architect: Ben Thompson Associates.

187. Illustration of a slab.

188. Illustration of shear resistance.

189, 190, 191. Carpenter Art Center, Harvard University, Cambridge, Massachusetts. Architect: Le Corbusier.

192, 193. Design Research Building, Cambridge, Massachusetts. Architect: Ben Thompson Associates.

194, 195. Eastern Airlines Terminal, Boston, Massachusetts. Architect: Yamasaki.

196, 197, 198, 199, 200. Employment Security Division Office Building, Boston, Massachusetts. Architect: Paul Rudolph.

201. Folded plate roof, Durham, North Carolina.

202. Illustration of folded plate.

203. Folded plate roof, Durham, North Carolina.

204. Folded plate restraint.

205. Community Services Building, New Haven, Connecticut.

206. Title slide.

207. Illustration of an arch and a parabola.

208. Illustration of an arch and post-and-beam.

209. Exhibition Hall, Rome. Designer: Pier Luigi Nervi.

210. Harvard University Stadium, Cambridge, Massachusetts.

211. Illustration of hinging of arches.

212. Harvard University Stadium, Cambridge, Massachusetts.

213. Title slide.

214. Short barrel vault.

215. Illustration of short barrel vault.

216, Athletic Building, Harvard University, Cambridge, Massachusetts.
217.

218. Church, Raleigh, North Carolina.

219. Illustration of long barrel vault.

220, St. Louis Airport Terminal. St. Louis, Missouri.
221, Architects: Yamasaki, Hellmuth, Obata and Kassabaum, Inc.
222.

223. Interior of Eastern Airlines Terminal, Boston, Massachusetts.

224. Rolls of corrugated steel.

225. Short barrel vault.

226. Title slide.

227. Dome, Chapel Hill, North Carolina.

228. Sea urchins.

229. Illustration of dome action.

230. Traditional dome.

231. Exhibition Dome, Norfolk Convention Center, Norfolk, Virginia.

232. Astrodome, Houston, Texas.

233. Dome, Chapel Hill, North Carolina.

234. Title slide.

235. Shells.

236. Illustration of shell thickness.

237. Eggshell.

238. Kiln, Greensboro, North Carolina. Architect: John MacRae.

239. Illustration of hyperbolic parabola.

240, Kresge Auditorium, Massachusetts Institute of Technology,
241. Cambridge, Massachusetts. Architect: Saarinen.

242, Sydney Opera House, Sydney, Australia.
243,
244.

245. Shells.

246. Title slide.

247. Cables.

248. Illustration of a parabola.

249. Illustration of cable slope.

250. Illustration of cable flexibility.

251. Suspension bridge.

252, 253. Institute of Contemporary Art, Boston, Massachusetts.

254, 255, 256. Dorton Arena, Raleigh, North Carolina. Engineer: Nowicki.

257. Bicycle wheel.

258. U. S. Pavilion, United States Exposition, New York City.

259, 260. Ingalls Hockey Rink, Yale University, New Haven, Connecticut. Architect: Saarinen.

261. German Exhibition, Expo '67, Montreal. Architect: Frei Otto.

262. Cable guy wire.

263, 264. German Exhibition, Expo '67, Montreal. Architect: Frei Otto.

265. Umbrella.

266. German Exhibition, Expo '67, Montreal. Architect: Frei Otto.

267. Title slide.

268, 269. Pneumatic structure, Harvard University, Cambridge, Massachusetts.

270. Illustration of pneumatic structure.

271. Pneumatic structure, Raleigh, North Carolina.

272. Pneumatic structure, Harvard University, Cambridge, Massachusetts.